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

[Ron Quan](#) - April 10, 2018

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 Vin for **Figures 29 to 32** has a very low output source impedance (e.g., < 50 Ω) and is preferably provided by an amplifier such as an op amp.

For each circuit, R17 = R18 to provide one path on unity gain inverting amplification via Vout and Vin. On another path with C14, the FET (Q2B in **Figures 29, 30, and 31**; and U2A in **Figure 32**), and R19, form a voltage controlled variable frequency high pass filter, via Vphase_mod.

Figure 29 shows a JFET voltage controlled phase shifting circuit.

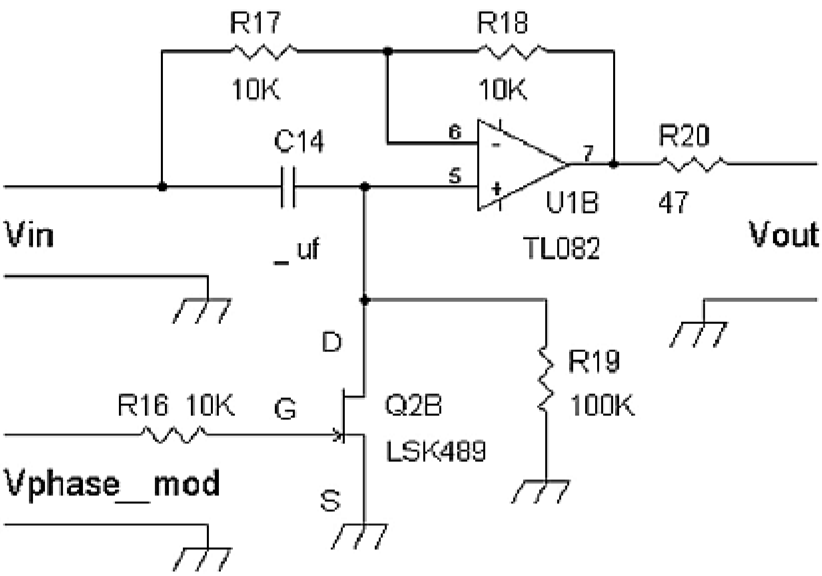

Figure 29 A basic phase-shifting circuit with a JFET and Vphase_mod normally connected to a

voltage source referenced to ground.

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

φ = - [180 degrees – 2arctan(f/f_c)]

Where $f_c = 1/(2\pi RC)$ and R = Rds||R19 and C = C14

With Rds = drain to source resistance of the FET, Q1B.

For example if $f = f_c$, then φ = - [180 degrees – 2arctan(1)] = - [180 degrees – 2x45 degrees] or φ = -90 degrees.

As an example, Vphase_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, Vp. For an LSK489, the Vp can be – 3.5 volts. For example, -3.5 v ≤ Vphase_mod ≤ 0 v.

The input signal, Vin 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 Rfb with the FET voltage controlled resistors (Q2B, Q2B, and U2A) shown in **Figures 30 to 32**.

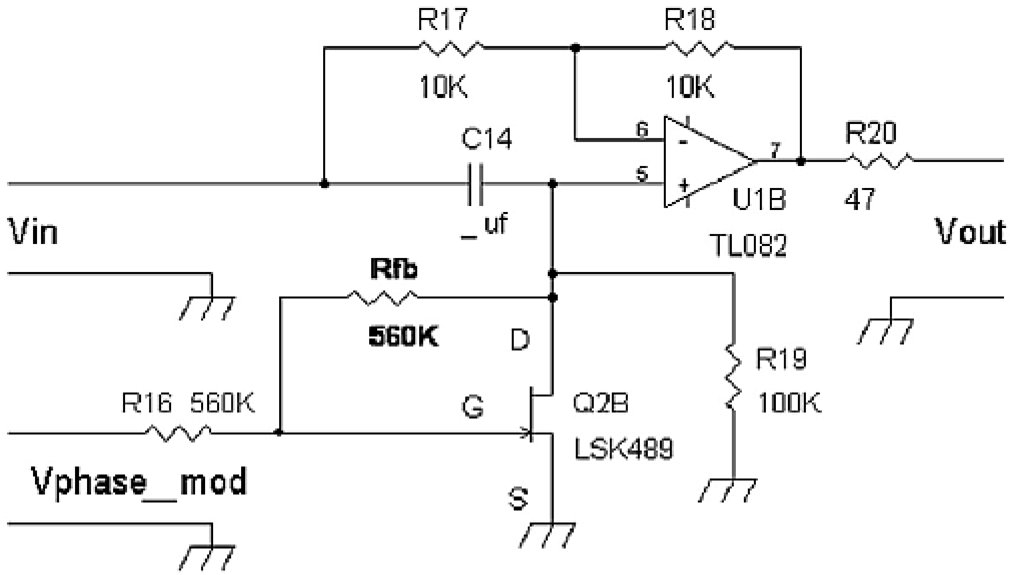

Figure 30 A lower distortion phase shifting circuit used a feedback network Rfb and R16.

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

φ = - [180 degrees – 2arctan(f/f_c)]

Where $f_c = 1/(2\pi RC)$ and R ~ Rds||R19||(**Rfb** + R16) and C = C14

With Rds = drain to source resistance of the FET, Q2B.

Because the feedback network reduces the control voltage range by 50%, we have to increase the Vphase_mod's voltage range:

2Vp ≤ Vphase_mod ≤ 0 v

For an LSK489, Vp can be – 3.5 v, or

2(-3.5 v) ≤ Vphase_mod ≤ 0 v, which is:

-7.0 v ≤ Vphase_mod ≤ 0 v

An example Vphase_mod = DC bias voltage plus an AC modulating signal.

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

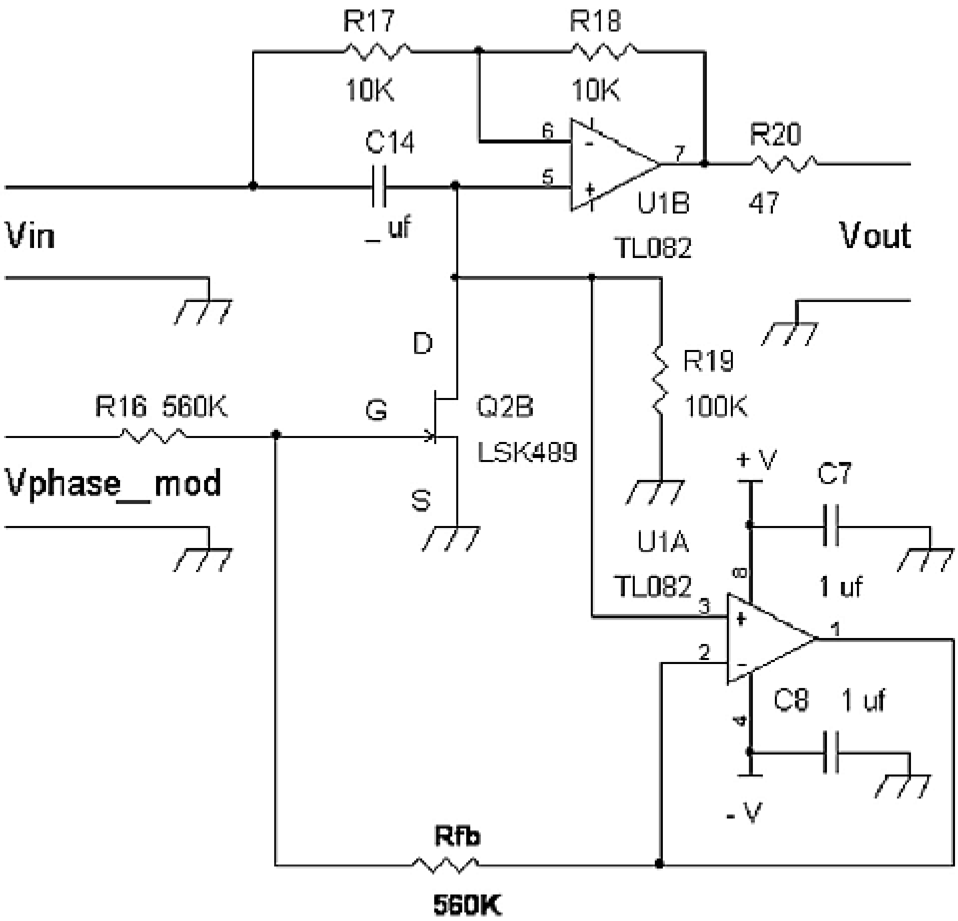

Figure 31 A voltage controlled phase shifting circuit with feedback and buffer amplifier U1A.

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

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

Where $f_c = 1/(2\pi RC)$ and R ~ Rds||R19 and C = C14

With Rds = 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 Vphase_mod to the output Vout is eliminated.

Again the control range is:

2Vp ≤ Vphase_mod ≤ 0 v

For an LSK489, Vp can be – 3.5 v, or

2(-3.5 v) ≤ Vphase_mod ≤ 0 v, which is:

-7.0 v ≤ Vphase_mod ≤ 0 v

An example Vphase_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.

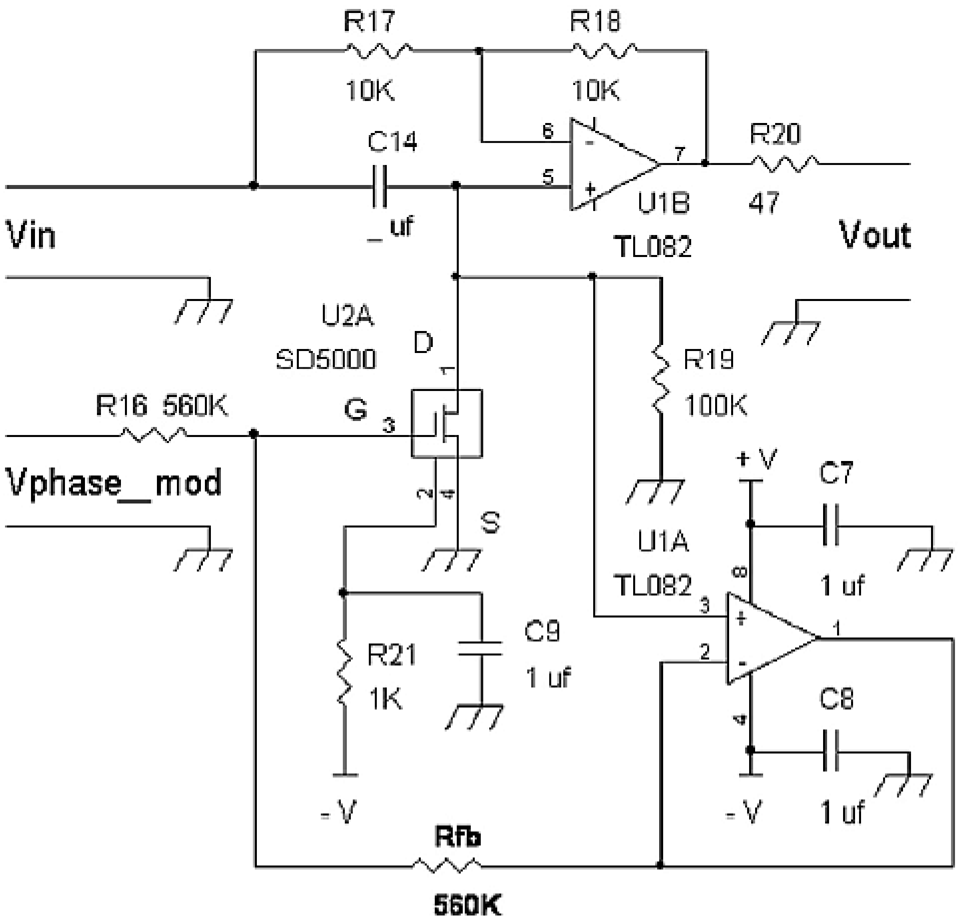

Figure 32 A MOSFET phase shifting circuit with feedback network and buffer amplifier for reduced distortion.

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

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

Where $f_c = 1/(2\pi RC)$ and R = Rds||R19 and C = C14

With Rds = drain to source resistance of the FET, U2A

Because MOSFET U2A is an enhancement device, Vphase_mod > 0 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 Vphase_mod to 8 volts.

That is,

+0 v ≥ Vphase_mod ≥ +8.0 v

An example Vphase_mod = DC bias voltage plus an AC modulating signal.

Note again the buffer amplifier, U1A, prevents Vphase_mod from cross talking into Vout.

For musical effects, sometimes distortion is desired, and Vin's amplitude can be increased beyond 500 mV peak to peak to add distortion at Vout 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 Vin 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, *Cvar*, provides a variable resonant frequency given by

$f_{res\_var\_C} = 1/[2\pi\sqrt{(LCvar)}]$

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

$f_{res\_var\_L} = 1/[2\pi\sqrt{(Lvar)}C]$

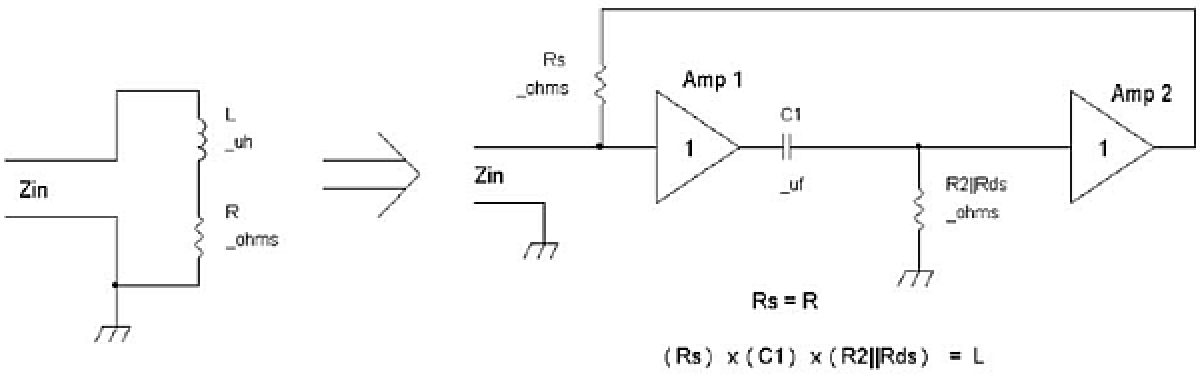

Figure 34 An inductor on the left side is implemented as a simulated inductor (gyrator) on the right side.

The gyrator's inductance L = Rs x C1 x R2||Rds, where R2 is shown in **Figures 35 to 39** and Rds is the drain to source resistance of an FET in **Figures 35 to 39**. The equivalent inductor series resistance R is Rs.

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 Zin of the gyrator at DC is just a resistor, Rs, 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.

Zin = R + jωL , where j is an imaginary number with $j = \sqrt{(-1)}$, and $j^2 = -1$, and ω = 2πf, with f = frequency in Hz.

As ω = 2πf → infinity, Zin → infinity

Now does the gyrator behaves in a similar manner when the frequency → infinity?

On the right hand side the capacitor C1 has an impedance of 1/jωC1. As ω = 2πf → infinity, the impedance of C1 → 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 Rs, top side is the same AC voltage as the input signal voltage at the input of Amp 1 and bottom side of Rs. Because there are equal AC voltages on both sides of Rs, there is no signal current flowing into Rs. This is the same as if there is an open circuit going into Rs for the input side. Because input impedance of Amp 1 is infinite, we then find that no AC current flows at the Zin point, which means Zin = infinite impedance when ω = 2πf → 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.

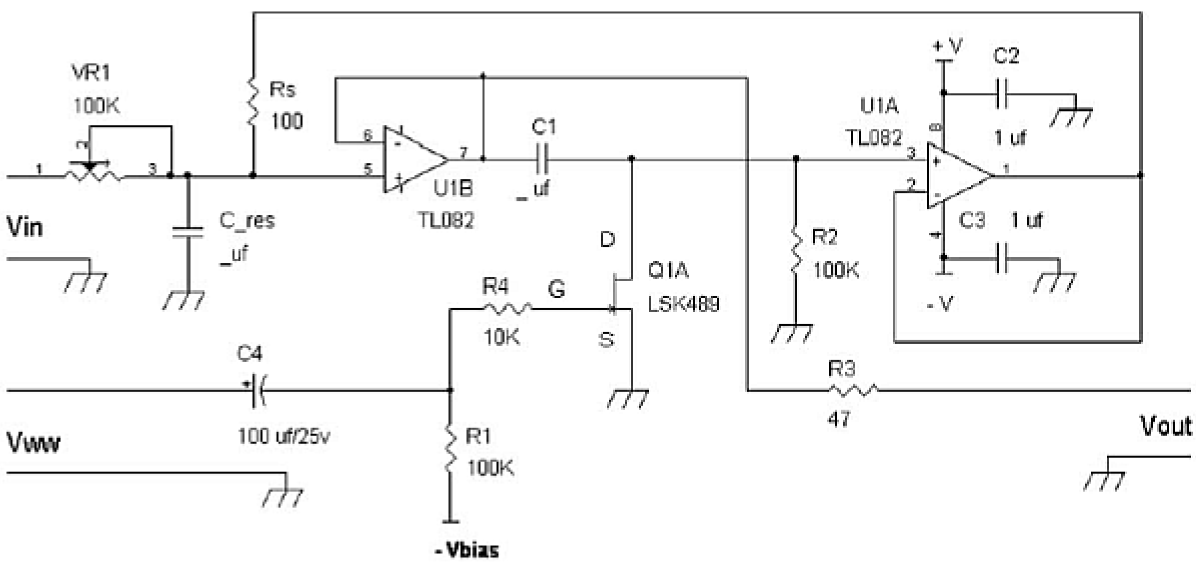

Figure 35 An active band pass filter circuit with a voltage controlled gyrator.

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 Rds||R2 in **Figure 34**. Rs, which = 100 Ω in **Figure 35** is analogous to Rs in **Figure 34**. Since the gyrator forms an inductor to ground at the pin 5 U1B/Rs junction and ground, a parallel LC circuit is implemented with capacitor C_res connected to the gyrator and to ground. Vin drives a series resistor via variable resistor VR1 to the parallel LC tank circuit where L = Rs×C1×R2||Rds 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, Vout, will not affect the band pass filter's characteristics such as loaded Q or gain. Note that R3 is 47Ω isolates the op amp from a capacitive load that may otherwise cause U1B to oscillate.

To reiterate, at the junction of Rs and pin 5 of U1B, we have an inductor referenced to ground. The inductance L = Rs x C1 x R2||Rds. The capacitor in parallel to this L is C_res.

For example if L = 1 H and C_res = 0.033 uf, the resonant or peak amplitude frequency is

$f_{res} = 1/[2\pi \sqrt{L(C\_res)}] = 1/[2\pi\sqrt{(1H)(0.033\ uf)}] = 876\ \text{Hz} = f_{res}$

Vin is the input signal (e.g., musical note) with Vww 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.

Vbias sets Rds 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, Rs, and the frequency of interest, f_{res}.

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

For example, if f_{res} = 1000 Hz and L = 1 H, and Rs = 100Ω, 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 >> 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 uf,

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

Suppose we set VR1 = 25KΩ = R, then

$Q_{loaded} = 2\pi f_{res}\ RC\_res = 2\pi(876\ \text{Hz})(25\text{K}\Omega)(0.033\ \text{uf})$

$Q_{loaded} = 4.54$

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

BW_{-3dB} =192.9 Hz

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

Rs = 100Ω

C1 = 1 uf

Rds from the FET Q1A = 11KΩ

R2 = 100KΩ

Rds||R2 = 11KΩ ||100KΩ = 10KΩ

L = Rs x C1 x Rds||R2 = 100 x $1x10^{-6}$ x 10,000 H = 1 H = 1 Henry

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

As a suggestion only for the following frequencies, f_{res}, with Rds = 10KΩ, Rs = 100Ω, R2 = 100KΩ we have:

f_{res} ≥ 700Hz, L = 1 H via C1 = 1 uf

200 Hz < f_{res} < 700 Hz, L = 2.2 H via C1 = 2.2 uf

f_{res} < 200 Hz, L = 4.7 H via C1 = 4.7 uf.

Note that C1 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**).

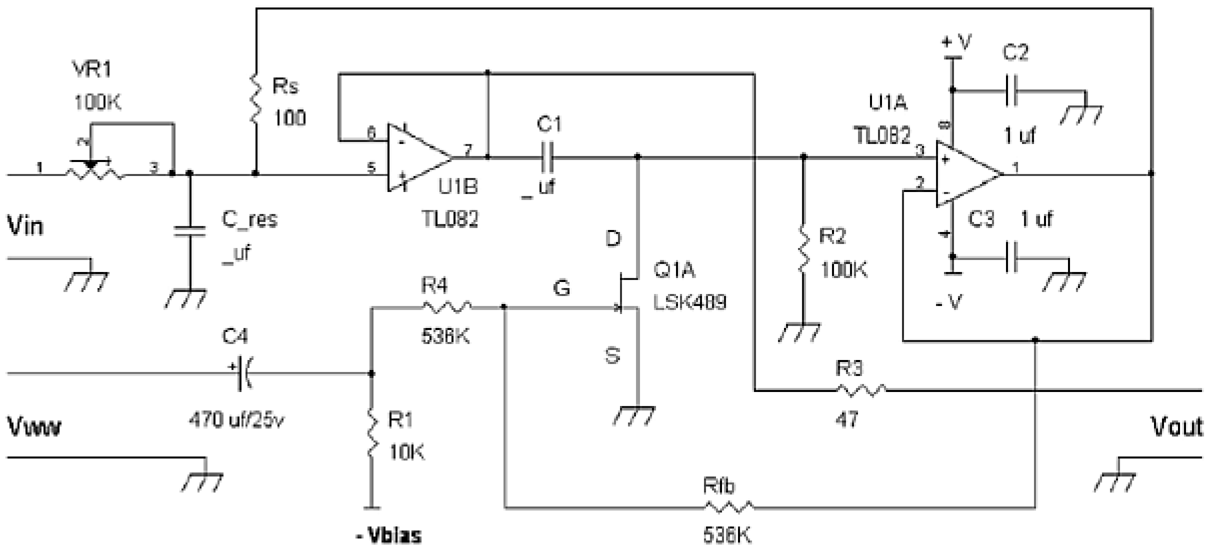

Figure 36 A more linear voltage controlled resistance via feedback resistor Rfb.

For a more linearized Q1A R_{ds} resistance, the Vin input levels can be larger. However, the bias voltage, -Vbias and Wah-Wah signal, Vww will need to be doubled due to the Rfb and R4 voltage divider circuit.

Figure 37 shows a basic voltage controlled band pass filter using an enhancement mode MOSFET. It has similar characteristics as **Figure 35**. However, note the bias voltage is positive for the N Channel MOSFET, U2A. Again, as a reminder Vin should be < 150 mV peak to peak in for **Figures 37, 38 and 39**.

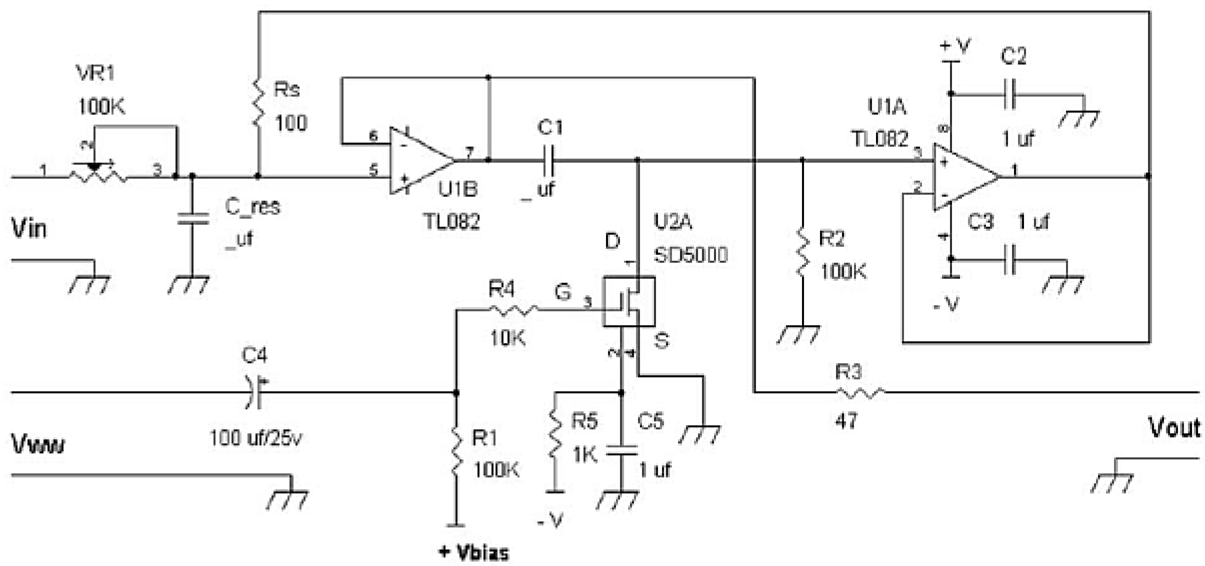

Figure 37 A MOSFET voltage controlled band pass filter circuit.

Essentially this circuit is similar to N Channel JFET version in **Figure 35**. Just keep in mind that the bias voltage + Vbias will in the range of 0 to + 4 volts for MOSFET U2A.

Again, we can take advantage of voltage follower U1A to linearize U2A's drain to source resistance (**Figure 38**).

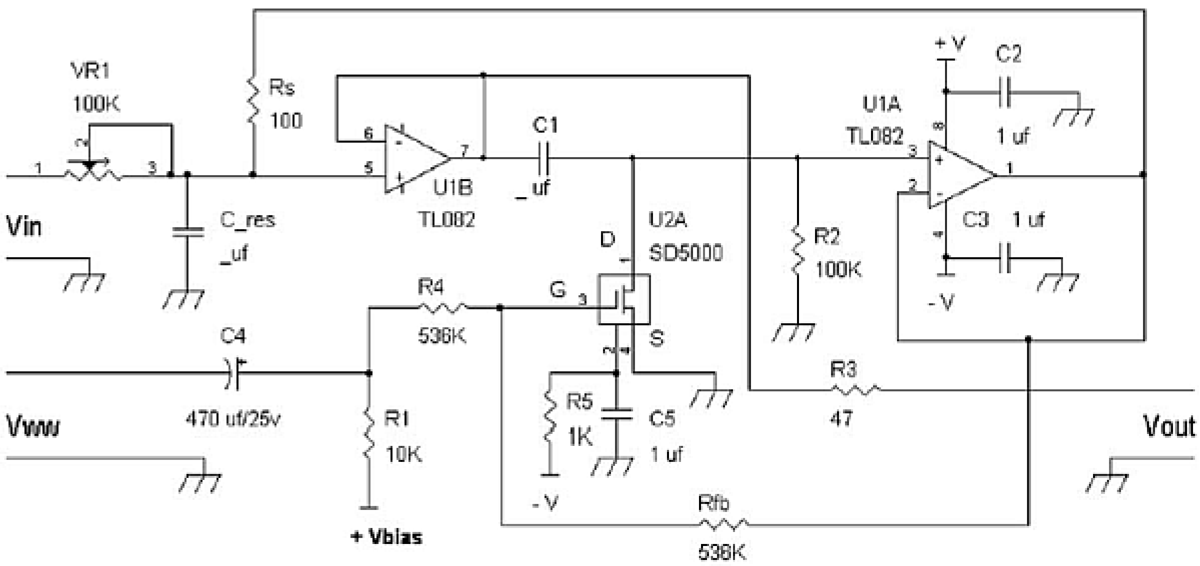

Figure 38 A voltage controlled MOSFET band pass filter with linearized drain to source resistance.

The bias voltage and Wah-Wah signal, Vww, will need to be doubled in range because of the voltage divider circuit Rfb and R4.

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

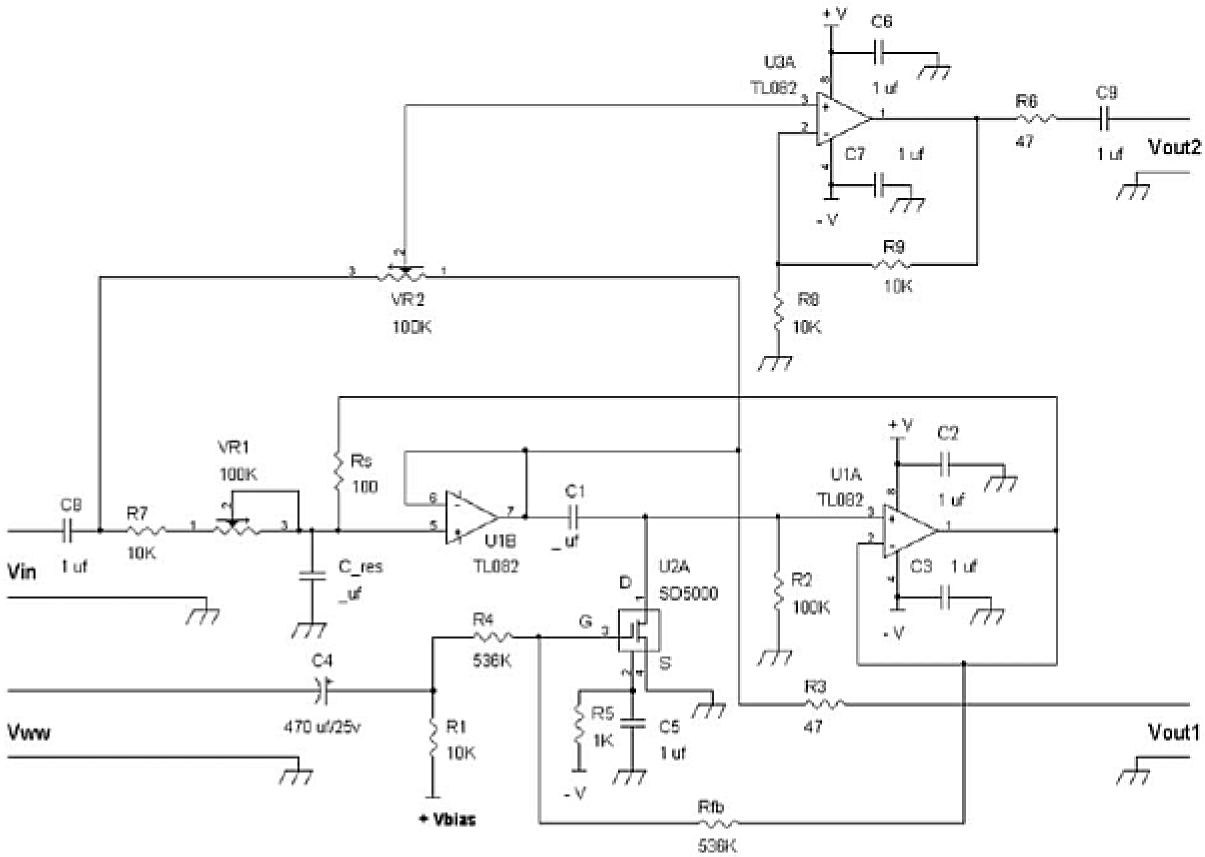

Figure 39 A blend control pot VR2 allows mixing part of the input signal with the band pass filter’s output.

By adding VR2 a blend of both the input signal plus the voltage-controlled band-pass filtered signal is provided via Vout2. By adjusting VR2 you can output via Vout2 all of Vin, or a mixture of Vin 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.

More from this series:

- A guide to using FETs for voltage controlled circuits, Part 1
- A guide to using FETs for voltage controlled circuits, Part 2: N-Channel JFET attenuator circuit with feedback
- A guide to using FETs for voltage controlled circuits, Part 3: FET modulator circuits and VGA design

Related articles:

- Use a photoelectric-FET optocoupler as a linear voltage-controlled potentiometer
- Building a JFET voltage-tuned Wien bridge oscillator
- EE + music theory = confusion
- Pedal effect circuit design: getting started