EEE226 Amplifiers

Hamish Sams

December 5, 2017

Abstract

This report explains the use of op-amps and transistors in the application of amplifiers and the use of passive components to create a 10x probe.

1 Introduction(10%)

This report is based around the use of components to create amplifiers. This doesn't mean specifically positive gain amplifiers as we also talk about probes and their calibration. The aims of this report/lab are to understand why and how probes are built as they are and why we must calibrate them. We must also be able to understand and calculate component values for basic op-amp and transistor amplification circuits. Objectively from this lab we must output working circuits that amplify our signals and be able to explain any distortions or issues with the specific circuits used.

2 Background(20%)

2.1 Coaxial/BNC cables

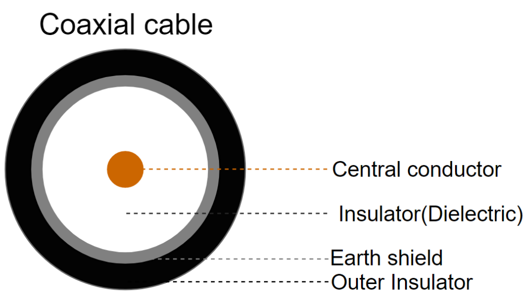

Figure 1: Cross-sectional diagram of a Coaxial cable (used for BNC cables)

Typical cables used are BNC cables(Name of the connector) which are connected together using Coaxial cable which, as shown in Figure 1, has a central conductor separated from the cylindrical ground using a insulator. The idea of the design being any signal that interferes with the central conductor must also pass through the earth shield(just like a twisted pair). This is also useful as if the insulator is broken the cable shorts before being able to electrocute the user hopefully allowing the system to detect the issue.
Unfortunately with two conductors separated nearby this creates a parasitic capacitance in parallel and a series resistance from the copper carrying the signal (Equivalent circuit shown in Figure 3).
Where R_C is the resistance of the coaxial cable (negligible when dealing with the majority of circuits) and C_C is the capacitance of the cable(negligible for low frequencies and DC).

2.2 Realistic oscilloscope

Unfortunately, the pain doesn't stop there, we are using an oscilloscope to measure our values and as always with wires in close proximity there is a parasitic capacitance and on top of that our

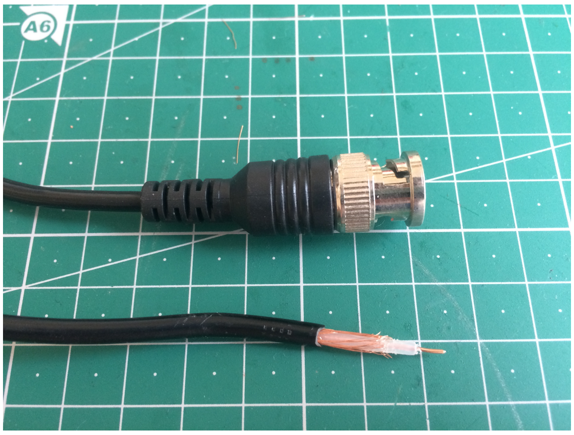

Figure 2: Cross-sectional picture of a Coaxial cable

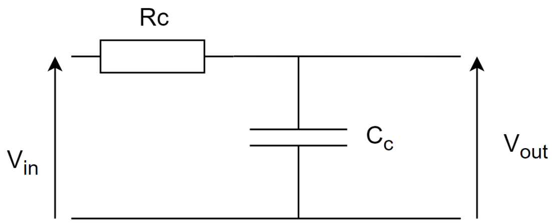

Figure 3: Equivalent circuit of a coaxial cable.

oscilloscope has an input resistance (usually $1M\omega$), this allows things such as our 10x probes to work whereas for a 1x system we would like this resistance to be infinite. so our oscilloscope can be modeled as seen in Figure 4.

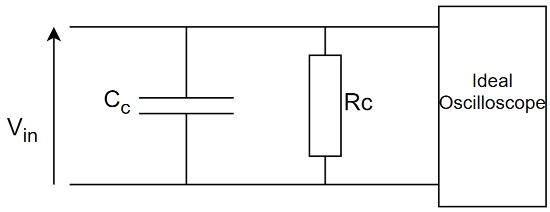

Figure 4: Realistic Oscilloscope

2.3 Rise and fall time/ Time constants

As expected, when we attach a capacitor to a voltage source it takes a time to charge up but as the capacitor charges its opposing voltage increases caused by the charge accumulating on the plates meaning, less voltage is over our resistance which then in turn means less current, which then means slower charging (shown in equation 1).

$$V(t) = CV_i(1 - e^{(}\frac{-t}{\tau})) \tag{1}$$

τ is the capacitor/resistor network time constant where $\tau = RC$

Looking at the equation if $t = \tau$ we see that the output voltage is 63% of the input voltage assuming the capacitor is initially discharged completely. What this means is every τ the voltage has increased on the capacitor by 63% of the voltage applied compared to the voltage the capacitor has already stored. This means the voltage will technically never actually reach 100% of the

supplied voltage with an asymptote around the point. This is shown in Figure 5.
Also in this figure we can see our rise time of the system (Shown in red) which is the time taken for the capacitor to charge from 10% to 90% as we know they system shouldn't be able to actually reach 100%, looking at our capacitor equation we can input we want the time to reach 90% minus that from time to get to 10% and we can see that this time is given by $t = 2.2\tau$ useful to work out capacitances or resistances in our circuit if we measure our rise time. Red- Top and bottom 10%

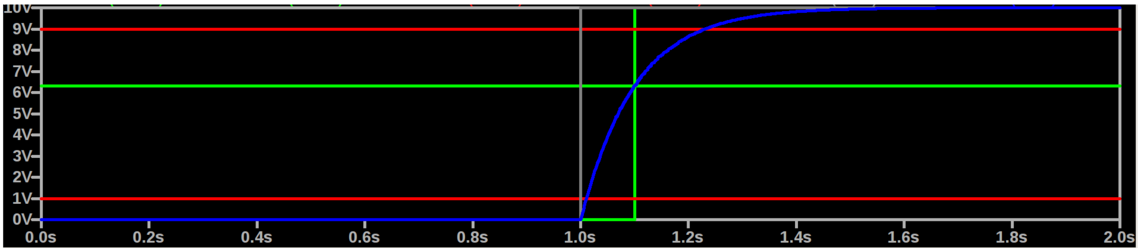

Figure 5: Capacitor charging over a fixed resistor

(Rise time)
Green - τ = RC and that voltage a t τ is 63%
Blue - The voltage over the capacitor over time
Gray - Input voltage (on/off step)

2.4 Op-amps

2.4.1 General

The familiar opamp is a very useful component in ac and digital systems due to its properties including huge input impedance, low output impedance (relatively) and its enormous open loop gain. The general equation for an opamps output voltage is shown in equation: 2

$$V_o = A_v(V_+ - V_-) \tag{2}$$

This equation tells us that the difference of the inputs V_+ and V_- is amplified by a factor A_v which is our huge open loop gain(Which is frequency dependent), this open loop gain in frequency dependent based on the construction of the op-amp shown in equation 3

$$A_v = \frac{A_0}{1 + j\frac{\omega}{\omega_0}} \tag{3}$$

A_0 is the open-loop DC gain; ω_0 is the -3dB point of the circuit ($2\pi f_0$). This frequency dependence is due to the internal capacitance and inductance of the circuit and therefore we can expect the familiar -20dB/Decade roll-off graph as show in Figure 7
From the equation we can tell when $\omega = \omega_0$ our system is at the corner frequency (imaginary = real) therefore we can expect a 45 degree phase shift just like an other RLC network.
If we look at our equation we can tell that if $1j\frac{\omega}{\omega_0}$ the magnitude is then given by $|A_v| = \frac{A_0}{\sqrt{2}}$

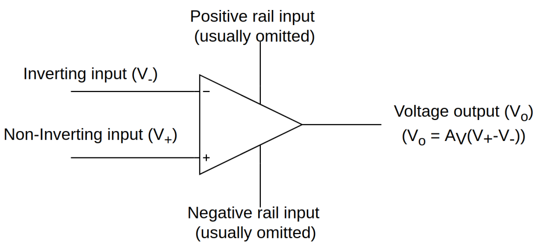

Figure 6: Basic op-amp layout

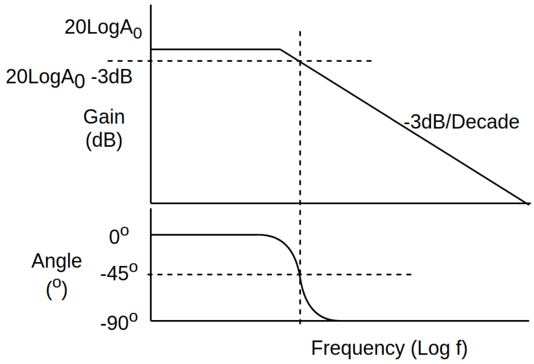

Figure 7: Op-Amp frequency based gain and phase shift.

2.4.2 Fixed gain amplifier

This circuit is generally crafted using the circuit diagram shown in Figure 8 and using our equations previously described in our op-amp section if we assume $A_v >> 0$ we can use this to ignore tiny imperfections and just say that $V_+ = V_-$ as long as our system is using negative feedback (imperfections are put into the inverting input altering the output which intern reduces the error) using this we can say that our circuits gain is given by $G = \frac{R_2+R_1}{R1} = 1 + \frac{R_2}{R_1}$, this equation can then be used so we can set a fixed gain for our circuit (Non inverting). It is important to realize the difference between negative and positive feedback as we cannot use this with positive feedback(this amplifies error back into the input meaning the system could never act as an amplifier and can only exist in saturation, as shown ahead in Schmitt triggers).

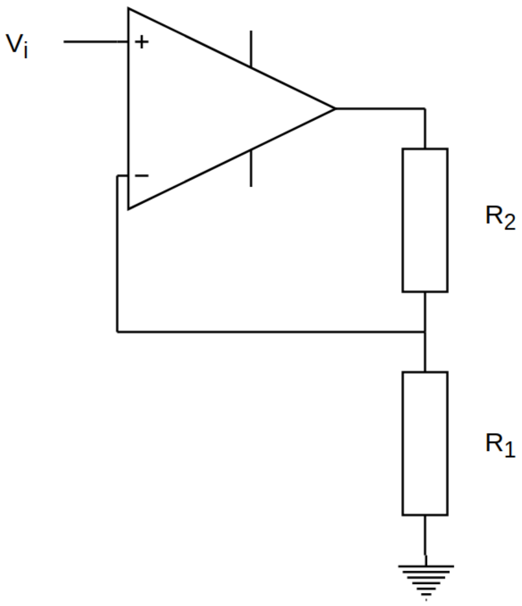

Figure 8: Fixed gain, negative feedback amplifier

2.4.3 Integrators

As expected from the name this circuit is designed around integrating the input. The general solution to this is shown in Figure 9. While looking confusing to begin with this circuit can be intuitive when through about in terms of what a capacitor does. Initially it's best to look at the circuit in terms of current, if we assume the op-amp takes no (or negligible) current then for the system to function the current from the input must equal the current back from capacitor (as the system uses negative feedback and v_+ is attached to ground therefore v_- must be a virtual earth) if our input has 5V over the resistor like In our case the output must therefore satisfy the capacitors voltage to equal this current so therefore our circuit must follow the equation shown in equation 4

$$\frac{5}{R} = C\frac{dv}{dt} \tag{4}$$

and as the voltage over the capacitor is our output we get that $\int \frac{5}{RC}dt$ is our voltage out and therefore given by an integral.

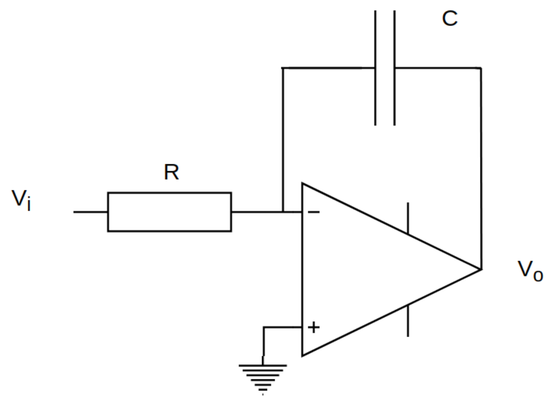

Figure 9: Integrator circuit.

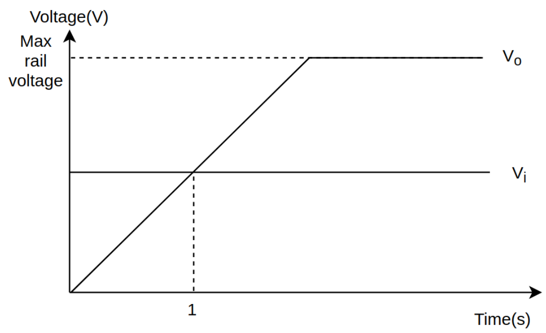

Figure 10: Integrator circuit input vs output for dc

2.4.4 Schmitt trigger

Unlike all other op-amp circuits talked about here this is the odd one out in the fact that it uses negative feedback and therefore only exists in saturation whether that be positive or negative depends on the input(technically the system could exist in between but the op-amp is far too sensitive for this to be particularly useful). Looking at the equation 2 we can see that if v_- is always 0 then the output will be the input multiplied with the open loop gain which in turn would increase the input voltage once again amplifying by the open loop gain and in no time at all(in the slew rate of the op-amp) the amplifier should switch to the saturation voltage and vice versa for negative voltage.

2.5 Transistors

Transistors are by far the most used component throughout all electronics mainly due to the 4 states they can exist in (On,Off,Forward active, Reverse active) in our case we are talking about the amplification property and so we will ignore the other states. For a transistor to be in the correct bias the voltage on the collector must be higher than the base voltage which must be in turn larger than the emitter voltage. In terms of diodes formed by the NPN doping the base emitter must be forward biased with the collector base diode reverse biased.

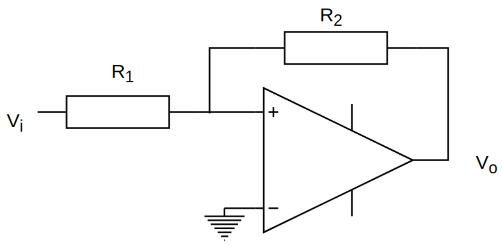

Figure 11: Schmitt trigger circuit.

2.5.1 Crossover Distortion

Crossover distortion is a type of distortion caused by transistors turning on and off in a push pull transistor layout. This distortion is based on the small voltage change not biasing the internal diodes fast enough, this means that we can fix this distortion by either increasing the voltage on the input to switch the diode or have the transistors never turn off therefore never have to switch on and off. An example of crossover distortion can be seen in Figure 12. As expected, due to the distortion being caused by the diode biasing we can see there is a drop of about 0.7V on the output compared to the input meaning in HV systems it is much less noticeable compared to a low voltage electronic situation.

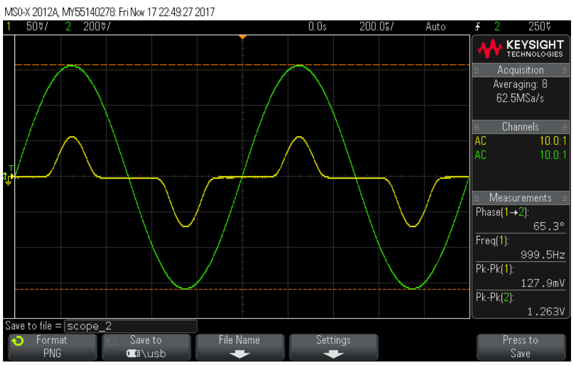

Figure 12: Crossover distortion graph

3 Theory(30%)

3.1 1x Probe Parasitic components

Using our knowledge of coaxial cables, realistic oscilloscopes and time constants of systems we can use an equivalent circuit to see what's truly going on, for this we will assume any wire resistance is negligible giving us Figure 13.

(Figure 13: Where C_i is the input capacitance and R_i is the physical internal input resistor of the oscilloscope.)

As our system is being used to calculate an unknown capacitance C we cannot ignore our parasitic capacitors C_C andC_i we must instead calculate them to negate them.We can also add C_c and C_i to give us C_m to simplify the circuit further as capacitors in parallel add together (logical when you think about what a capacitor really is).This circuit on its own cannot help us too much as we can only get a capacitors value in terms of another so two measurements must be taken(this time using two lots of oscilloscope connections to double the value of C_m(remember capacitors in parallel add up) to create simultaneous equations using the rise time of the device.(Bear in mind R_i is ignored when dealing with rise time as it is in parallel).

When dealing with fall time the circuits capacitors are no longer being charged through R they are now discharging through R in parallel with R_i so we can use the same method of simultaneous

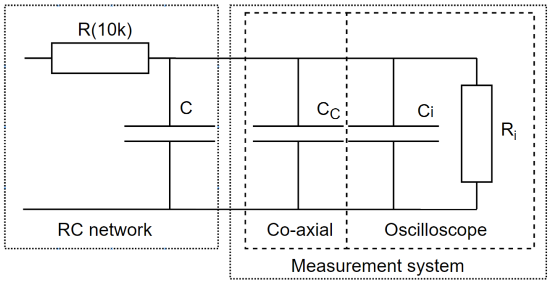

Figure 13: Equivalent circuit of a probed RC circuit.

equations using one and two lots of measurement parasitic components remembering this time R_i and $\frac{R_i}{2}$.

3.2 10x Probe Parasitic components

A 10x probe ideally splits the voltage applied to it to a tenth of the voltage, this is done by using a simple potential divider but as we know the coaxial cable used to connect the two has an unwanted capacitance shown in Figure 14

The figure shows that for DC the voltage gain is:

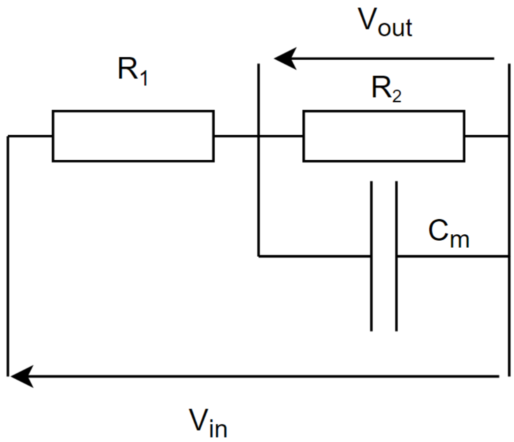

Figure 14: Potential divider with parasitic capacitor

$$G = \frac{R_2}{R_1 + R_2} \tag{5}$$

If our resistor in the oscilloscope in $1M\Omega$ (R_2) we can see that our R_1 needs to be $9M\Omega$ to get a gain of $\frac{1}{10}$ but now imagine our circuit for high frequency AC signals (where C_m is a short) we can see our probe wouldn't pick up any voltage as is it poses no resistance in comparison to R_1. So to solve this we must use two potential dividers one for AC signals and one for DC signals shown in Figure 15.

As this capacitor C_m isn't really controllable and can change from environment to environment it is necessary to be able to tune this capacitor so that the capacitors follow the equation, Equation,5 (with resistors swapped for capacitors) aka, 9 times C_m for a 10x probe.

3.3 Square wave generator

For a basic square wave generator (basic meaning negligible current sourced) we can attach the output of an integrator to the input of a Schmitt trigger as shown in Figure 16. You may notice the resistor at the output of the Schmitt trigger, this is designed to reduce the voltage output to 5V(/-5V) for the input to the integrator. There is also two zener diodes which are used to make

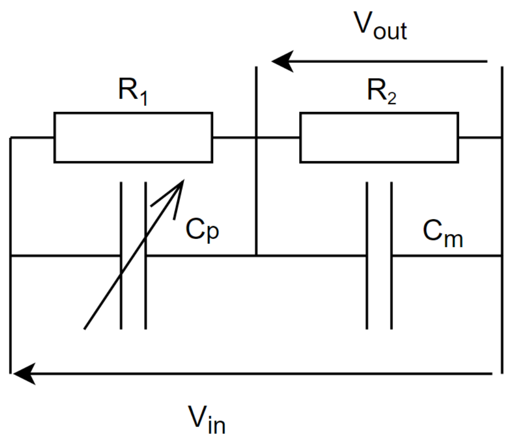

Figure 15: AC and DC potential divider

sure the output is constant at 5V as the forward voltage is 0.7V like a normal diode and the reverse breakdown voltage of the zener is 4.3V meaning our circuit keeps the voltage on the rail between 5V and -5V. This resistor that limits the voltage output also limits the current down to 10mA and so our system cannot draw more than this so we must design our values around this. Our 10mA must be split between the zener voltage control our integrator and our Schmitt trigger, i chose 2mA for both the integrator and Schmitt trigger stages allowing the majority of current to be left over for the zeners and to make the numbers nicer. If our voltage over R is 5V(/-5V) with 2mA flowing we can easily calculate the resistance using ohms law. The resistors $R_1$and R_2 both pass 2mA with 15V and 5V over each respectively and once again this resistance can be calculated using ohms law. Our capacitor must be designed around our system parameters, we must match the capacitor current to the resistance and so we use equation 6 to calculate the capacitance as our current must equal 2mA and our $\frac{dv}{dt}$ is given by our required output, as we want a 1kHz square wave our capacitor will charge for 500uS before discharging and it will charge by 5V using this we can calculate our capacitance and therefore have all of our circuit parameters. This circuit works by integrating our square wave signal output meaning the integrator outputs a sawtooth(back to back triangles), these triangles oscillate the input to the Schmitt trigger meaning each triangle outputs a square wave from the Schmitt trigger.

$$I = C\frac{dv}{dt} \tag{6}$$

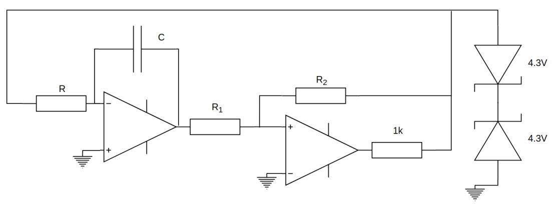

Figure 16: Square wave/sawtooth generator

3.4 Audio amplifiers

The first idea to create an audio amplifier is to use a fixed gain amplifier as previously explained in section 2.4.2. this is a brilliant solution for medium-high impedances as the op-amp greatly increases the output current and can be created to have a large voltage gain and therefore a large power gain. Op-amps are designed to have little if any noticeable distortion as the output can swing to any value to linearly amplify the signal. The only issue with this is an average op-amp is very limited in its current output meaning for any speaker demanding more that about 100mA it's not going to be able to supply those kinds of currents.

If our speaker system requires more current to be driven into it to function properly the next idea is to use a transistor setup where in a class B amplifier (as seen in Figure 17 transistors turn on and off in opposition so one (the NPN on the top) deals with positive voltages and the other (PNP) amplifies for the negative voltages, this is preferred over the use of a class A amp as for a class A amp there is huge power dissipation which is wasted even when there is no signal being amplified. The issue with using this class B amplifier is the crossover distortion caused by the transistors turning on and off as talked about in 2.5.1, this isn't a huge issue if we are using larger voltages but is very noticeable in the low voltages as shown in figure 12, from the previous section we know the crossover distortion is based on voltage and therefore if we increase the voltage while this crossover distortion is happening we can counteract this effect and so we can use an op-amp to check our output voltage against the input signal and therefore have the signal accuracy of the op-amp mixed with the power of the transistors as seen in Figure 18. If our system requires that no op-amps could be used we can also use a class AB amplifier, it is classified as this because there are two transistors still, one for positive and one for negative just like a class B but they are both constantly on like in a class A amplifier. This is done simply by adding a bias between the two transistors where Vin is seen in figure 17.

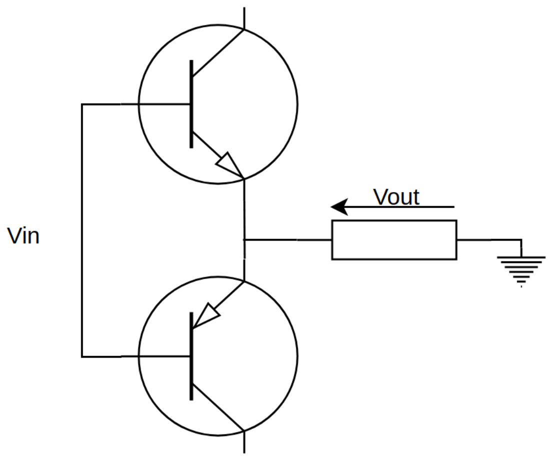

Figure 17: Class B amplifier

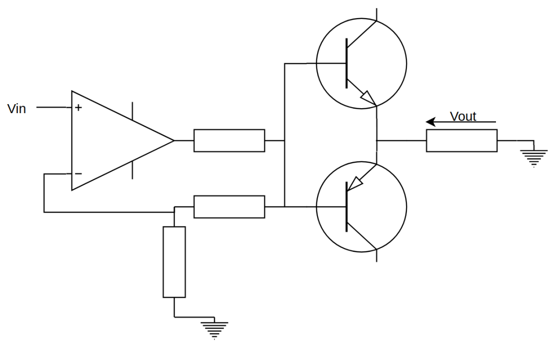

Figure 18: Class B amplifier with op-amp crossover reduction

4 Method and Results(10%)

For method and results i am going to focus on the material in lab 2 (fixed gain amplifier).
For a fixed gain op-amp circuit we must design our system to appear first order (an input must must appear identical on the output but generally effected by a gain) aka a linear system. In our case we will look at the gain bandwidth product of the system, equation wise we can prove that at any point our gain-bandwidth product (gain*frequency) has nothing to do with our resistors

and so is constant with the op-amp. Our tests performed by using two separate gains on the same op-amp proved this. Therefore if our system has a gain of 1 then the bandwidth is equal to the GBWP.We can quickly get a value by setting our gain and then increasing the frequency until the output is at the -3dB point which in turn can be used to quickly calculate the bandwidth of the device due to this linearity which values of which are proven in the lab.

5 Discussion(10%)

5.1 Probes

Because we can counter the capacitance of our probes we can start dealing with higher frequencies assuming we have attenuated our probe correctly, this doesn't mean we can use these probes at any frequency as any tiny difference means a large change in the signal measured.

5.2 Signal Generator

As our circuit is based around keeping all of the current inside the loops it's very difficult to use this system as a source of power without a buffer as the current drawn would change the circuits effects drastically. However if our circuit is used with low current systems with resistances in the mega ohms this should be fine. Basically we could say our system is good as a signal generator but not as a power source.

5.3 Amplifiers

The amplifiers we have looked at in section 3.4 each have their own advantages and disadvantages, the first we looked at was the simple fixed gain amplifier of Figure 8. This circuit was good because it had absolutely no noticeable gain and only would become distorted if the output needed to be more than the voltage rail value supplied. The issue is when you try to drive a low impedance load the op-amp can't deliver enough current and will saturate after about 100mA. Our next solution is to use a transistor to deliver the amplification as they can deal with much larger currents now the only issue being high power loss when using a class A amplifier or crossover distortion using a class B amplifier, class AB amplifiers are a crossover between the both where you have less power loss and no crossover distortion but still a large power loss and even more components. We then used a op-amp on the input to supply voltage to the transistor which negated the transistor crossover distortion by increasing the voltage as fast as it can (slew rate) until the output is amplified correctly as seen in Figure 18.

6 Conclusions(10%)

6.1 Probes

For any probe you must follow Equation 7, for the values shown in Figure 15. If this is satisfied then we can use this to probe up to much higher frequencies without a large drop-off but unfortunately this doesn't work for huge frequencies and there is still a drop off.

$$G = \frac{R_m}{R_p + R_m} = \frac{C_m}{C_p + C_m} \tag{7}$$

6.2 Signal generator

For our signal generator we can find out our component values through current analysis with the information we know about integrators and Schmitt triggers from previously stated information. This system works perfectly as long as we are taking a negligible amount of current from the system to not stop any of the three stages (integrator, Schmitt trigger, zener regulator) working properly and therefore cannot be used to supply current but is good at supplying voltage.

6.3 Amplifiers

We saw that there were lots of different ways to amplify our signals each with their advantages and disadvantages the first of which our op-amp fixed gain amplifier which is good due to the tiny error in signal amplification but not so good because of the low output current. To solve this we moved onto transistor based amplifiers, with these circuits we must design our system perfectly to meet the bias criteria. First of all a class A amplifier where one transistor does all of the amplification is good as there is little distortion assuming the input voltage isn't changed drastically but this system wastes a lot of power. Instead we looked ad a class B amplifier where the power consumption is less but we must think about the crossover distortion. To get rid of the crossover distortion we could use a class AB amplifier which biases transistors to be on negating the crossover distortion but increases power waste. Finally we looked at a class B amplifier with an op-amp input which negates the crossover distortion, keeps the transistors off when not in use and has tiny signal distortion.

References