AN-ELECT1-LAB-2
Diode Applications Exploration

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Abstract
In this application note, we will be exploring the different kinds of diodes and diode applications. In general, diodes are electrical semiconductors that allow current to flow in one direction. There are a number of general applications for diodes, including rectifying AC voltage, as well as the use of LEDs for lighting and signaling applications. This application note will cover some of the theory behind diodes, as well as some practical applications for diodes in electronic circuits.

Introduction
Diodes are classified as semiconductors. They are devices that allow current to be driven only one way. Another way to describe diodes is whether they are forward or reverse biased. For example, Figure 1 below is a basic symbol of a silicon diode. In forward biased diodes, the current flows in the direction of the arrow, and in reverse biased diodes, the current flows the opposite direction of the arrow.

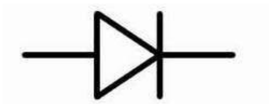

Figure 1. Diode Symbol

Diodes have two terminals – the anode and cathode. One way to think of it is that the anode is where the current flows in to, and the cathode is where the current flows out of. This defines the polarity of the diode. The anode is the positive end, and the cathode is the negative end. This is called forward bias. Reverse bias is the other way around; anode is negative and cathode is positive. Figure 2 below demonstrates the polarity as well as show how a diode looks like in real life; the light-colored strip on the cylinder is the cathode end. It is important to understand the polarity especially when building circuits.

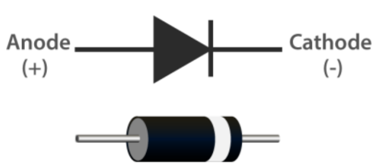

Figure 2. Diode Polarity

Diodes can also be classified as rectifiers. Rectifiers are electrical devices that will convert AC to DC by simply allowing only one direction for the current to flow. It is considered rectification because it basically straightens the current.

The current across a diode is known as the Ideal Diode Law [1]. The equation is a function of voltage, and describes the current going through the diode.

Equation 1: Ideal Diode Law

$$I = I_0(e^{\frac{qV}{kT}} - 1)$$

Where:
I = net current flowing through diode,
I_0 = saturation current,
V = applied voltage across the diode,
q = charge of an electron (1.602 x 10^{-19} coulombs),
k = Boltzmann's constant (1.38 x 10^{-23}),
T = absolute temperature, in Kelvin.

Silicon Diodes
Figure 2 from the Introduction section shows what a silicon diode symbol looks like in forward bias. The forward bias, internal barrier voltage (also known as the knee voltage) for silicon diodes is typically 0.7 V, and a good resistance is around 10 to 1 kΩ. In reverse bias, when measuring the current, will be 0 A, or close to it.

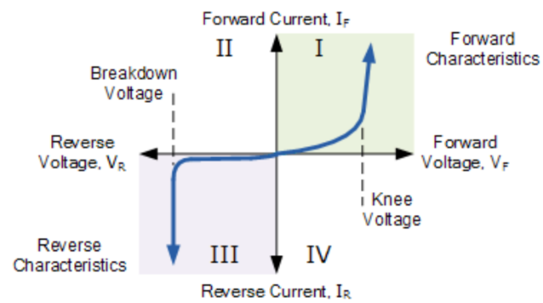

Figure 3. I-V Characteristics of Si Diodes

As shown above in Figure 3, the forward bias characteristics operate in the first quadrant of the I-V characteristics graph. The line gradually increases, but once it reaches the knee voltage, a phenomenon known as the "avalanche breakdown" occurs. This means that the current increases drastically in small increments of voltage.

In reverse bias, the diode operates in the third quadrant of the I-V characteristics curve. This demonstrates that the diode will continue to block current across itself in reverse bias, until the reverse voltage exceeds the breakdown voltage, when the current will rapidly increase in magnitude [2]. Silicon diodes are the most common type of diodes and are used in a wide variety of applications, which are listed below.

Rectifier
Rectifiers are devices that convert AC signals to DC signals. Normally, an AC circuit without a diode would simply show a sine wave when measuring the signal with an oscilloscope. However, when you insert a diode into your circuit, half of the sine wave would be missing, meaning the wave will not go negative, and instead will pause at zero volts until the period is complete. If you have a half-wave rectifier, the voltage will be zero whenever the non-rectified circuit would be negative, as shown below in Figure 4.

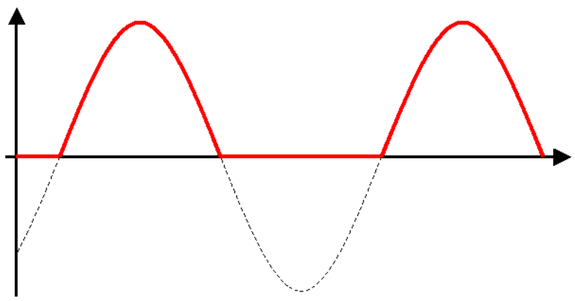

Figure 4. AC Signal After Half-Wave Rectifier

When you have a full-wave rectifier, the negative end of the signal is flipped to the positive end. In comparison to the half-wave rectifier, instead of having the signal pause at zero, the full-wave rectifier will go back up to full amplitude. In comparison to a non-rectified circuit, the negative phases will be flipped to the positive in a full-wave rectifier. This can be seen below in Figure 5.

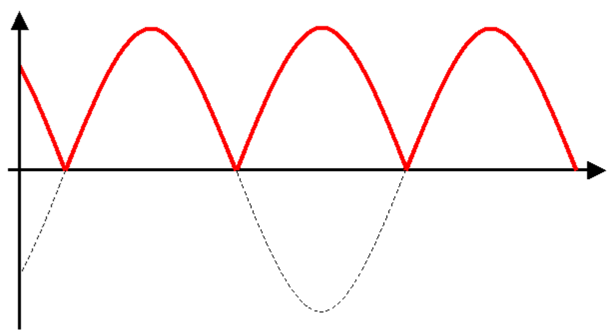

Figure 5. AC Signal After Full-Wave Rectifier

Clamp

Clamper circuits are devices that limit the output voltage to a specific range. This is also called a DC restorer. There are a few different kinds of clamper circuits: positive and negative clamper circuits.

The positive clamper circuit is a typical clamper circuit with the diode in forward bias. The output is that the signal is shifted to the positive portion of the graph. The schematic as well as the input and output signals of a positive clamper circuit can be seen below in Figure 6.

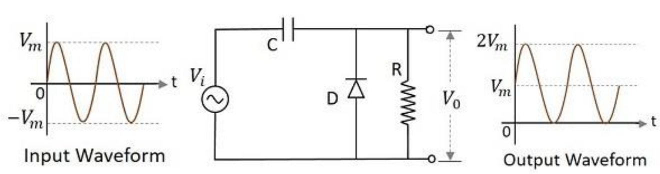

Figure 6. Positive Clamper Circuit

The negative clamper circuit is the same circuit, but the diode is reverse biased. The output is simply the input waveform shifted to the negative portion of the graph. This can be seen below in Figure 7.

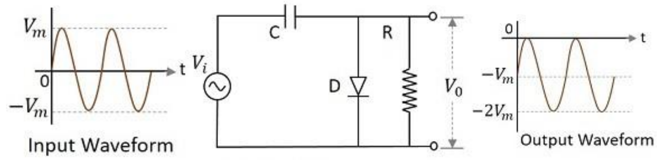

Figure 7. Negative Clamper Circuit

We can bias both circuits with a reference voltage, to shift the output waveform up or down (depending on if the reference voltage is positive or negative, respectfully). The waveform would be shifted to the amount of reference voltage added [3].

Doubler

The doubler circuit is a type of multiplier circuit that produces an output voltage that is two times larger than the input voltage. Below is Figure 8, showcasing the schematic of a simple doubler circuit.

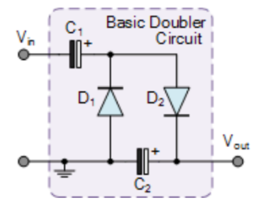

Figure 8. Basic Doubler Circuit

You can turn this into a tripler circuit by simply adding another capacitor and diode in the given pattern (which is essentially just a clamper). This doubler is considered a single, full stage of a multiplier circuit. A tripler circuit is simply a full stage and another clamper.

Non-Silicon Diodes

There are many types of diodes besides the standard silicon diode. Some of the alternatives to silicon diodes have been listed below.

Zener Diodes

Zener diodes are similar to Si diodes, where the electricity conducts from the anode to the cathode. However, when the predetermined reverse voltage is reached, the current will start flowing in the reverse direction. The symbol for a Zener diode is shown below in Figure 9.

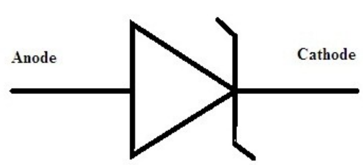

Figure 9. Zener Diode Symbol

The I-V characteristics of Zener diodes are shown below in Figure 10. This shows that, in reverse bias, when the diode hits the Zener breakdown voltage, the voltage remains almost constant for however much increase in current, giving you an almost straight, vertical line downwards [4].

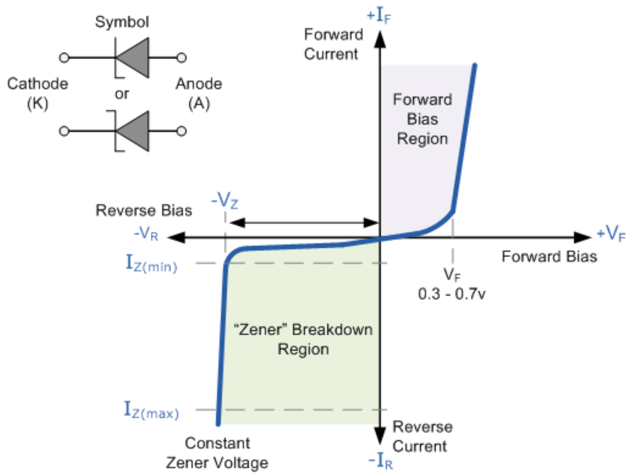

Figure 10. I-V characteristics of Zener Diodes

Schottky Diodes
The symbol for a Schottky diode is shown below in Figure 11.

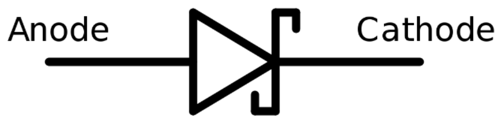

Figure 11. Schottky Diode Symbol

Schottky diodes are useful in low-power applications because the forward voltage is much smaller. The forward voltage, also known as the knee voltage, is about 0.4 V. Like Si diodes, when in reverse bias, the conduction immediately stops and starts to block current flow. The I-V forward characteristics of Schottky diodes and Si diodes are compared below, in Figure 12 [5].

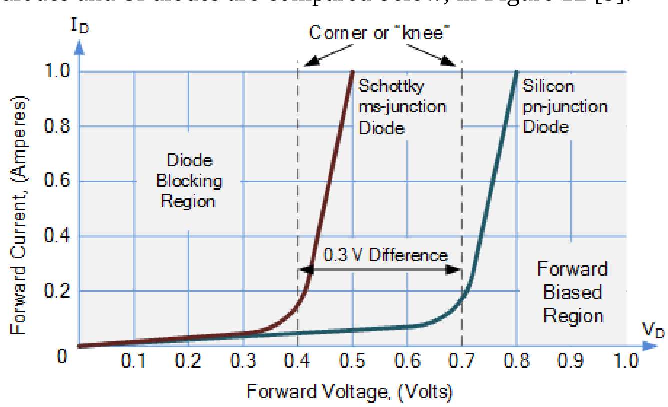

Figure 12. I-V Characteristics Comparison

Light Emitting Diodes (LEDs)
LEDs or light emitting diodes are used in a wide variety of applications where light emission is required. LEDs come in a variety of sizes from small surface mount packages to be used as indicators all the way up to large packages to be used in general lighting applications. LEDs are much more efficient at producing light than legacy technologies such as incandescent or fluorescent lighting. As you can see below in Figure 13, a standard 5mm through hole LED has two leads like any other diode, but it does not have a stripe for the cathode. For through hole LEDs, the cathode is denoted by a flat spot on the side of the LED, as well as the shorter of the two leads. Between these two markings, it should be easy to tell which lead is which of an LED.

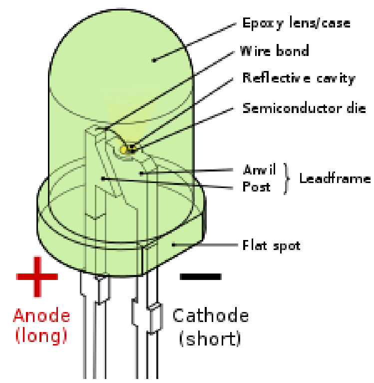

Figure 13. Anatomy of a through hole LED

LEDs are current controlled devices, meaning that the brightness of the LED is proportional to its forward current. For small LEDs, putting a current limiting resistor in line will allow you to regulate the current at a given voltage. This is acceptable for small LEDs such indicator lights on a coffee machine, but this method is not suitable for high power LEDs, such as LED light bulbs. The other way to control LED brightness, especially for high power LEDs is a constant current driver. Generally, a constant current driver IC and a current sense resistor is used to deliver a constant current, regardless of other system variables [6].

Application – Half Wave Rectifier
One application of diodes is a rectifier, which is used to convert AC voltage into DC voltage. A half wave rectifier works by taking in a sine wave (AC voltage) and "chopping off" the bottom of the wave, as shown earlier. A capacitor can be added to the output to smooth out the result. This can then then be regulated to the final DC voltage that you are looking to achieve. It is important to use a capacitor that is large enough such that it does not lose too much charge when the sine wave is off. In Figure 14 below, an example is shown of using a diode to create a basic half wave rectifier.

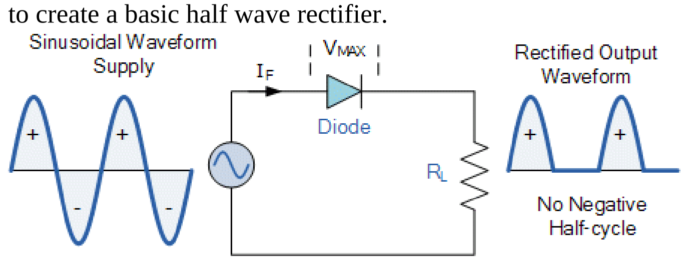

Figure 14. Half wave rectifier

As you can see from the figure, the negative half-cycle of the sine wave is removed from the output waveform. To make this waveform closer to a DC waveform, a capacitor can be added to the circuit across the load resistor to smooth out the resulting wave, as seen below in Figure 15. Note that Figure 15 also includes a transformer to step down the AC voltage before it is rectified.

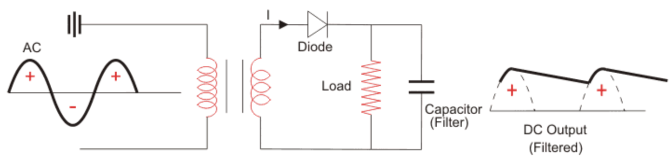

Figure 15. Half wave rectifier with filter capacitor

Using LTSpice, a half-wave rectifier was made and simulated, and the schematic is shown below, with the specifications used to simulate.

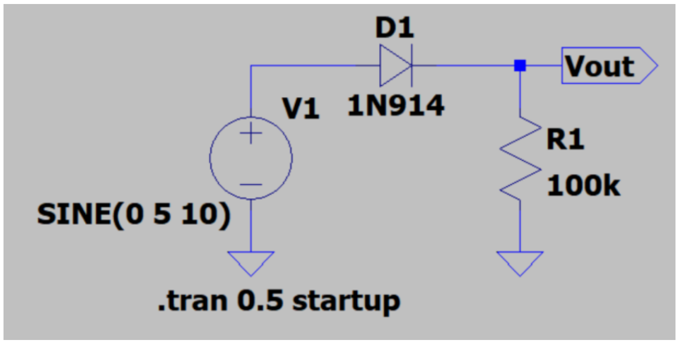

Figure 16. HWR Simulation Schematic

where the results are shown below. The green curve is the input signal, and the magenta curve is the output signal. The input signal's Y-axis is on the left, and clearly showing 2 V peak-to-peak. The output signal clearly does not go negative.

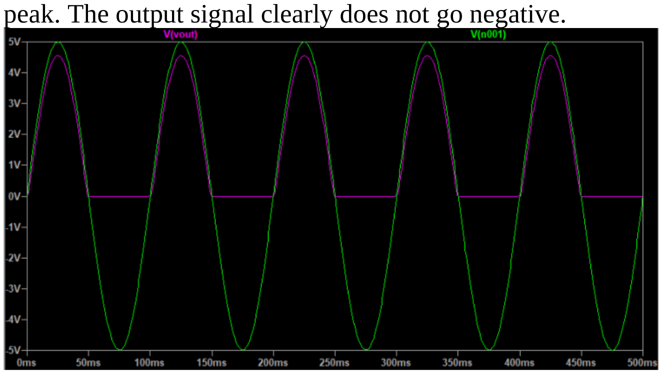

Figure 17. LTSpice Simulation, HWR

Application – Full Wave Rectifier

A full wave rectifier, otherwise known as a bridge rectifier, differs from a half wave rectifier in design by flipping the negative part of the sine wave to be positive. By adding a capacitor to the output, you can achieve a more DC like output with less ripple than a half wave rectifier. A capacitor is generally added across the load to help smooth the waveform. The capacitor also does not need to handle as much load, as it is being charged twice as often as in the half wave rectifier.

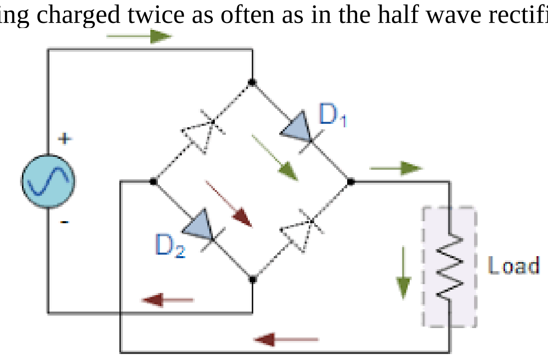

Figure 18. Full wave rectifier (no capacitor)

Application - Envelope Detector

An envelope detector is a circuit that outputs the envelope – or outline – of its input signal. Given a signal with a high enough frequency, the envelope detector will trace the top of an amplitude modulated signal and output that as a waveform. One application of envelope detectors is AM radio. The detector works by taking in an input RF signal with both the positive and negative curves, and it will output just outline of the positive curve. To demonstrate this theory graphically, see below in Figure 19 [7].

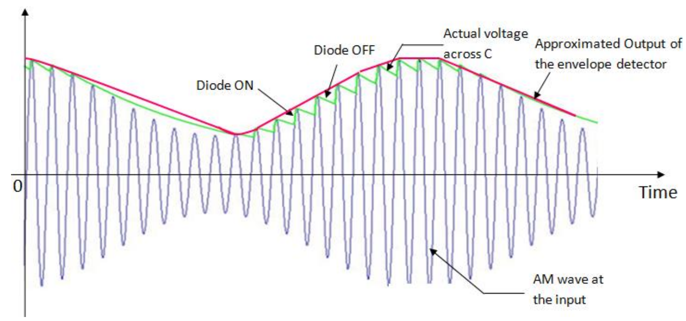

Figure 19. Envelope Detector in Theory

An envelope detector consists of a low pass filter and a rectifier. The filter is used to remove any noise/high frequency elements in the signal, while the rectifier will enhance the signal. The schematic for this can be seen below in Figure 20.

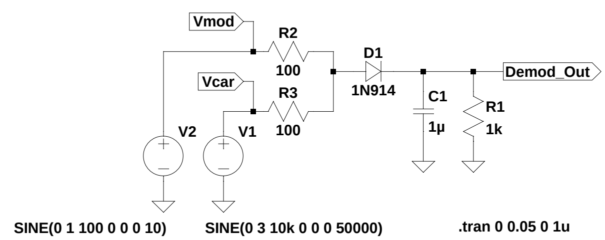

Figure 20. Envelope detector schematic

The output of the envelope detector is shown below. The dark background is the noise being filtered out by the low pass filter. The envelope is clearer to see when zooming in on the figure.

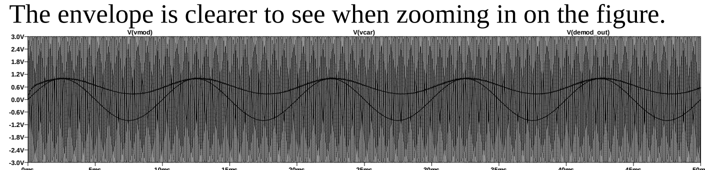
Figure 21. Envelope detector output

Filter (Storage Capacitor)

The filter is just a half-wave rectifier with a capacitor added in parallel with the resistor, as shown below, created in LTSpice.

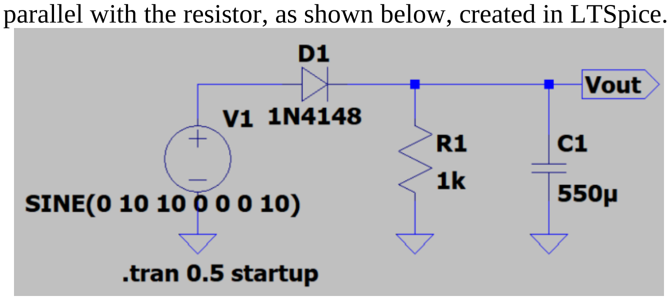

Figure 22. Filter (Storage Capacitor) Schematic

This circuit will produce very close to 1 $V_{p\text{-}p}$ ripple with a 550 µF capacitor, as shown below in the simulation window of LTSpice. The green curve is the input signal, with 10 V amplitude. The magenta curve is the output signal, V_{out}, which is across the capacitor.

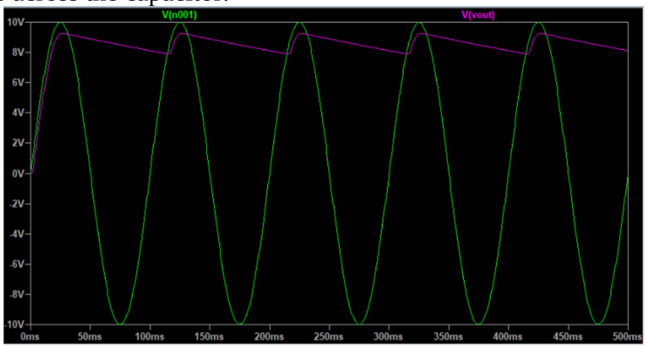

Figure 23. Half wave rectifier with filter, simulation

As seen above in Figure 23, the capacitor filter smooths out the final waveform – effectively filtering the signal. The capacitor charges up to the input voltage as the sine wave increases, and discharges as the sine wave falls. The capacitor in any given circuit should be specified so that the voltage output does not fall too low during the times the sine wave is in its negative half-cycle.

Zener Shunt Regulator

In a Zener Shunt Regulator circuit, the Zener diode shunts the current to ground. Shown below is a schematic of such circuit, created in LTSpice.

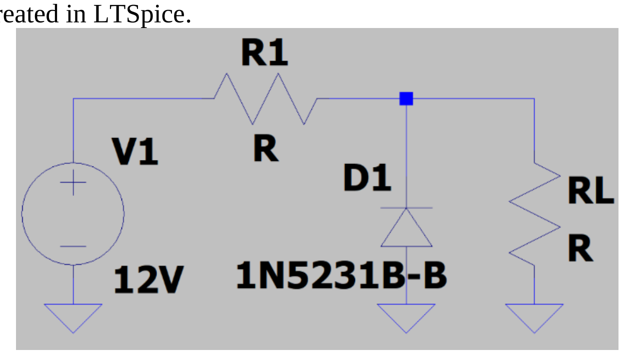

Figure 24. Zener Shunt Regulator Schematic

We can start with the fact that this diode, the 1N5231B-B, has a typical Zener voltage of 5.1 V, and the R_L needs a current of 100 mA. The load resistor then, using Ohm's Law, has a resistance of 51 Ω. However, since there is 100 mA going through it, using Ohm's Law again, $P = I^2R$, we will need a ½ W resistor, at minimum. We also know that this diode has a Zener current of 10 mA. This will allow us to calculate the resistance of R_1. The current across R_1 is equal to $100\,mA + 10\,mA = 110\,mA$. Because the Zener voltage is 5.1 V, we can do $12\,V - 5.1\,V = 6.9\,V$ across R_1. Which means, using Ohm's Law, we get a resistance R_1 of 63 Ω, which is a little more than ½ W so you will need a 1 W resistor. The total power can be calculated by multiplying the Zener voltage by the total current. P_z = (5.1V)(0.11A) = 0.561 W.

So we built this circuit in real life, and made measurements using a DMM. A variable power supply was also used. Below is a table of output voltages after adjusting input voltage.

Table 1. Line Regulation

V_{in} (V)	R_L (Ω)	V_{out} (V)
11.78	50	4.82
12	50	5.07
12.44	50	5.22

We can calculate the line regulation by doing $\frac{\Delta V_{out}}{\Delta V_{in}}$. Using this equation, we get a line regulation of 0.57.

To do load regulation instead of adjusting voltage, you adjust the load resistance. We kept the voltage at 12 V (give or take very few mV) and adjusted the load resistance from 50 **Ω** to 56 **Ω**, and we calculated the current. The results are shown in the table below.

Table 2. Load Regulation

V_{in} (V)	R_L (Ω)	V_{out} (V)	I_{out} (A)
12	50	5.07	0.10
12	56	5.18	0.09

To calculate the load regulation, you can do $\frac{\Delta V_{out}}{\Delta I_{out}}$. Using the data from the table above, we got a load regulation of 11 V/A.

Application – Precision Rectifier

By using op-amps with diodes, we are able to create a precision rectifier. A precision rectifier can be used for high precision signal processing tasks. Also known as a precision diode, the precision rectifier acts as an ideal diode. When a diode alone is placed on a voltage line, some voltage is list through the diode. By using a precision rectifier like shown below in Figure 25, we can eliminate this voltage drop, while still keeping the one directional voltage flow of a diode. How this works is the op-amp's non-inverting terminal is wired to its output through a diode. Since the op-amp is trying to keep it's inputs at the same voltage, it drives its output higher than V_{in} to compensate for the voltage drop across the diode. So far, this sounds like a voltage follower, but there are still diode characteristics. If V_{in} goes negative, the diode will not allow the current to flow, and thus the circuit maintains the main properties of a diode.

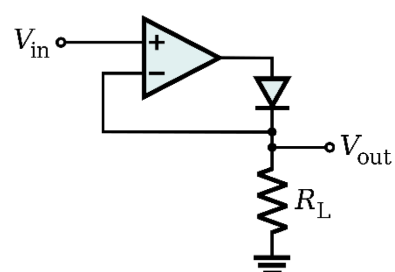

Figure 25. Simple precision rectifier schematic

Using the schematic above, the circuit was created and tested using an oscilloscope in XY mode. The expected output is a linear function with a slope being equal to one as this is an ideal diode. By analyzing the V_{in}/V_{out} transfer function as seen in Figure 26, we can confirm that the schematic above for a precision rectifier / precision diode works in the real world.

Figure 26. V_{in}/V_{out} transfer function

The largest issue with this schematic is speed. Op-amps are not high frequency devices, and such will take time to react to changes. Using an op-amp with a fast slew rate is ideal for this task, as it will help reduce lag time. A precision diode circuit can be used in place of a standard diode in many of the other applications described in this application note such as a precision envelope detector, or a precision clamp circuit.

References

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