Design of the Raspberry Spy NFC amplifier circuit

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Summary

This Document details the calculations necessary to design the Near-Field radio receiver on the Raspberry Spy Robot PCB, in order that the operating frequency can be adjusted.

1 License

Contents

2 Introduction

The Near Field Amplifier circuit was designed to be as easy to understand as possible, and its operation can be broken down into a series of stages. The overall circuit is shown in Figure 9 in the Appendix.

3 Input Decoupling

The input signal from the coil is roughly sinusoidal and oscillates about 0V. In order to amplify this directly, we would need to power the Op-Amp with both positive and negative supply voltages which are inconvenient to produce. It is much easier to power the Op-Amp between +5Vand 0Vand shift the input signal such that it is never negative. This is achieved by the circuit in Figure 1

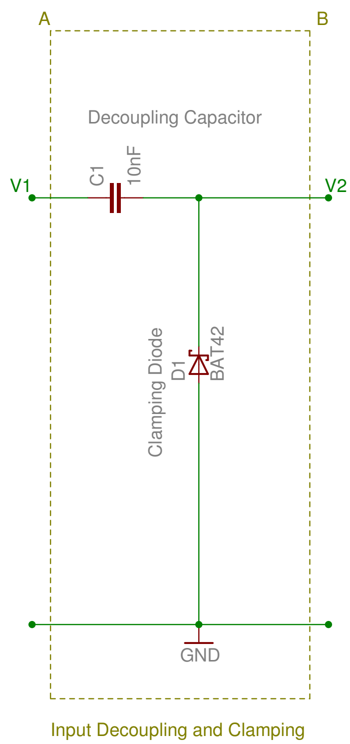

Figure 1: Input Decoupling and Clamping Stage

Assuming an input V_1 varying between $\pm v$:

- The decoupling capacitor C_1 blocks any DC component (impedance $\frac{1}{j\omega C} \rightarrow \infty$ as $\omega \rightarrow 0$)
- When V_1 is negative ($V_1 = -v$), the diode D_1 holds V_2 at 0 V by conducting from GND. The current from GND charges C_1 to $V_{C_1} = -v$.
- When $V_1 = +v$, diode D_1 does not conduct. Assuming the current drawn from the output terminals is small enough compared to the period of oscillation, C_1 will not discharge significantly and $V_2 = V_1 - V_{C_1} = 2v$ while V_1 is high.

4 Input Amplification

The next step is to amplify the input signal with the circuit in Figure 2

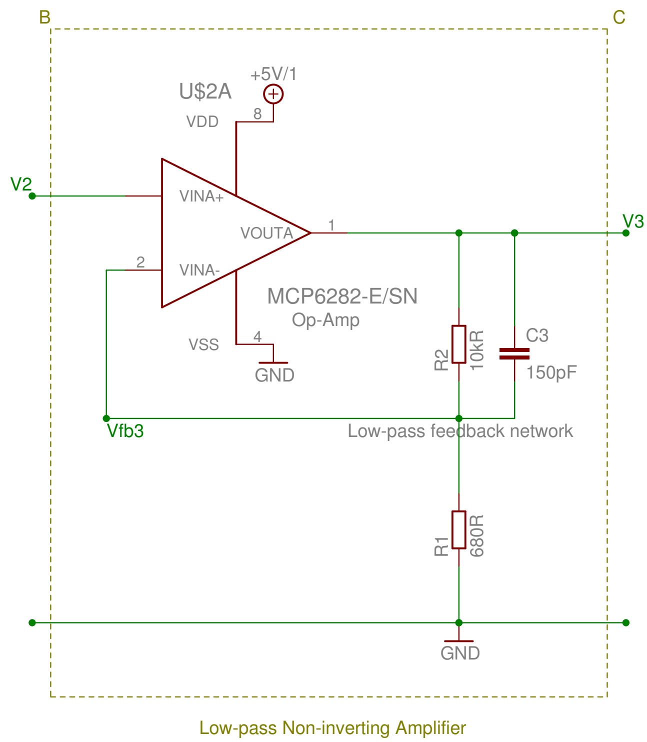

Figure 2: Input Amplifier

4.1 Mid-band Gain

At Mid-band (i.e the frequency we are interested in), C_6 behaves as an open circuit and may be neglected.

$$\text{For an ideal Op-Amp:} \quad V_{fb3} = V_2$$

$$V_{fb3} = \frac{V_3 R_1}{R_2 + R_1}$$

$$\text{so Gain} \quad G = \frac{V_3}{V_2} = 1 + \frac{R_2}{R_1}$$

Tests show that the voltage input from the coil is around 300 mV so to get output up to the 5V rail we need a gain of around 15. Therefore choose $R_2 = 10\text{k}\Omega$, $R_1 = 680\Omega$.

4.2 Choice of Op-Amp

To achieve a gain of 15 at 64 kHz with the output varying between 0 V and +5 V the minimum properties in Table 1 are required. Rail-to-rail operation is also desirable given the low voltage supply. The MCP628x series fits this specification.

Property	Minimum Value
Gain-Bandwidth Product (also known as Unity gain bandwidth)	1 MHz
Slew rate	2 V/μs

Table 1: Op Amp Properties

4.3 High frequency cutoff

The capacitor C_3 acts to bypass R_2 at high frequencies and thus reduce the high frequency gain to unity. The impedance of $R_2//C_3$ is

$$Z_{fb3} = \frac{R_2}{1 + j\omega R_2 C_3}$$

It is approximately true $\left(G \approx \frac{Z_{fb3}}{R_1}\right)$ that for the gain to be reduced by 3 dB from its mid-band value (half-power), the magnitude of the denominator must be equal to $\sqrt{2}$, thus

$$\omega_{-3\text{dB}} R_2 C_3 = 1$$

Choosing the cutoff frequency $f_{-3\text{dB}} = 84\text{kHz}$ we find

$$C_3 = \frac{1}{2\pi f_{-3\text{dB}} R_2} = 190\text{pF} \approx 150\text{pF}$$

5 High Pass Filter

The signal has now been amplified and low-pass filtered but there may still remain low frequency interference. This is removed in stage CD (Figure 3).

The effective resistance R_{eff} is taken as being equal to R_3 on the grounds that D_9 has negligible effect on positive signals (see Figure 9). The output voltage V_4 of this stage is thus given by the potential divider equation:

$$V_4 = V_3 \frac{R_{effective}}{R_{eff} + \frac{1}{j\omega C_2}} = V_3 \frac{1}{1 + \frac{1}{j\omega R_{eff} C_2}}$$

So for a lower -3dBfrequency $f_{-3\text{dB}} = 44\text{kHz}$:

$$2\pi f_{-3\text{dB}} C_2 R_{eff} = 1$$

$$\text{so} \quad C_2 = \frac{1}{2\pi f_{-3\text{dB}} R_{eff}} \approx 3.3\text{nF}$$

N.B. this needs to be recalculated if R_8 is altered.

6 Rectifier

Circuit DE in Figure 4 is used to re-clamp the output of the amplifier to have a minimum value of 0 V (the output otherwise does not quite reach the 0 V rail due to imperfect clamping on the input). D_3 in combination with C_2 performs the clamping. The rectifier diode D_9 may not seem necessary at first but it prevents current from flowing backwards into the amplifier feedback network when the envelope detector circuit is holding V_5 greater than V_4.

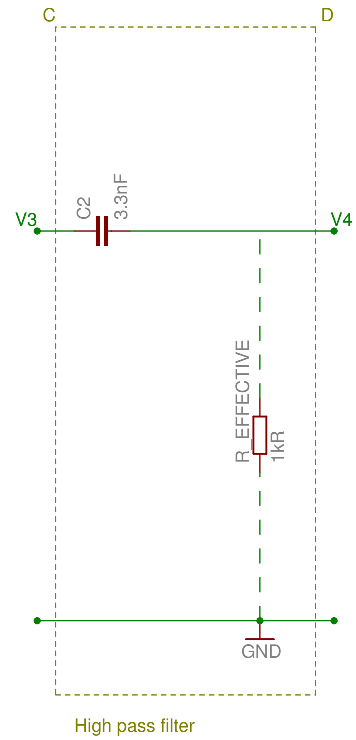

Figure 3: High Pass Filter

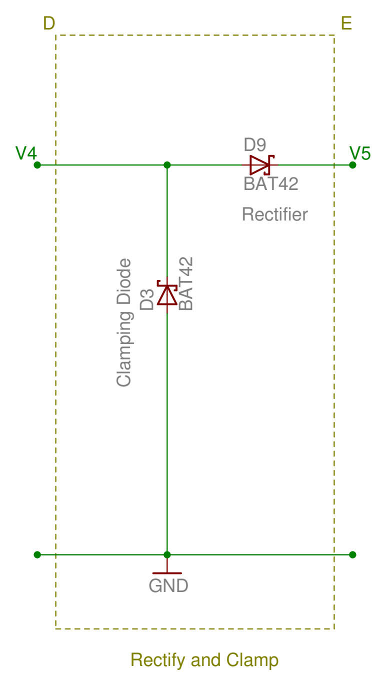

Figure 4: Rectifier and Clamping

7 Envelope Detector

The envelope detector EF shown in Figure 5 relies on the transient behaviour of a parallel RC circuit rather than the stead-state frequency response used in the filters.

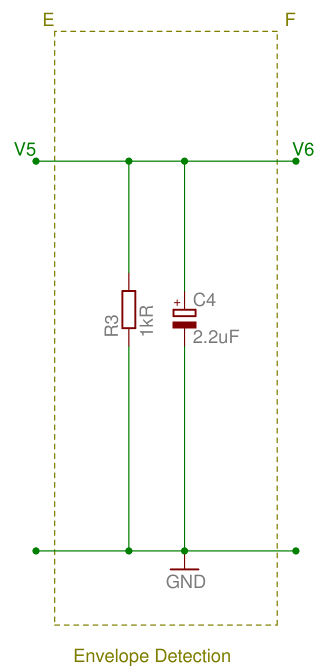

Figure 5: Envolope Detector

When the amplifier output at V_4 is high (+5 V), the capacitor C_4 will charge up almost instantaneously. When V_4 is low, diode D_9 prevents the flow of current back into the amplifier so C_4 must discharge through the parallel resistor R_3.

We must choose the time constant RC such that the carrier wave ripple is smoothed out but the envelope is still sufficiently sharp to detect the rising edge reliably. The circuit was designed for a 64 kHz carrier wave and a modulating signal of the order of 10 Hz (to allow for imprecise timing when bit-banging the GPIO pins from python).

Thus we need:

$$\begin{aligned} \tau_{carrier} << RC < \tau_{envelope} \\ \text{or} \quad \frac{1}{64 \times 10^3} << RC < \frac{1}{10} \end{aligned} \tag{1}$$

For minimum ripple, $RC \approx 0.002$ s was chosen (only just over one order of magnitude smaller than $\tau_{envelope}$). The maximum sustained output current of the MCP628x range of Op-Amps is 30 mA so R_3 must be greater than $\approx 180\ \Omega$. To fit both criteria we choose $R_3 = 1\ \mathrm{k}\Omega$ and $C_4 = 2.2\ \mu\mathrm{F}$

The speed of transmission can be increased by around an order of magnitude by reducing C_4 to 22 nF and C_{12} to 2.2 nF (see Section 10). This increases the ripple on the output slightly but the main limiting factor is the speed of the receiving python code on the Raspberry

Pi. Re-writing the code in C may allow higher transmission speeds but the inherent timing inaccuracies in non-real-time Linux make this more difficult than on a micro-controller.

8 Envelope Amplifier

The envelope detector increases significant attenuation so the output must be amplified again with the non-inverting amplifier stage FG in Figure 6.

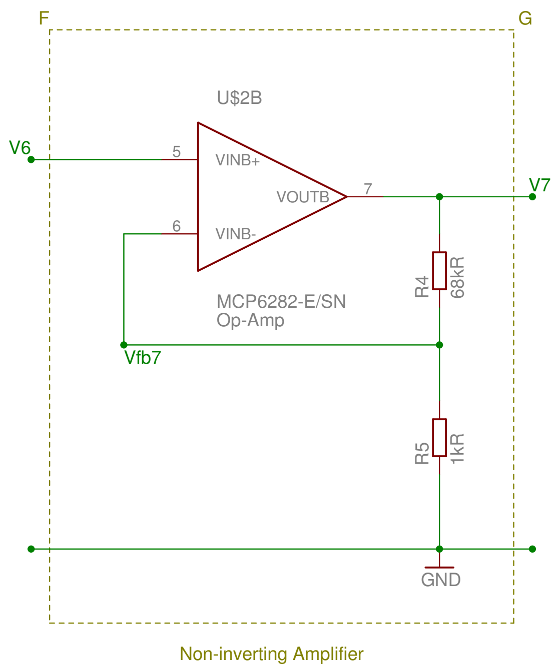

Figure 6: Envelope Amplifier

Resistors $R_4 = 68$ kΩ and $R_5 = 1$ kΩ are selected to give a gain of 70, ensuring the output clips to the +5 V rail. Almost any Op-Amp capable of running from a +5 V/0 V supply would be suitable here as the frequency of the signal to be amplified is so low. However the spare pins on the MCP6282 are used for convenience.

9 Potential Divider

The GPIO pins of the Raspberry Pi are not 5 V tolerant so the potential divider GH in Figure 7 is used to reduce the "high" voltage from 5 V to 3.3 V.

10 C_{12}

C_{12} was added to remove noise spikes when the circuit was built on solderless breadboard. It may not be necessary at all on the PCB.

11 Coil and range

Experiments show that a 60-70mm diameter coil of around 30 turns of 0.2mm enamelled wire works well (the coil may be circular or square as in Figure 8).

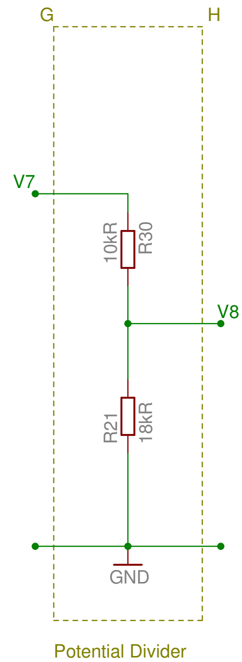

Figure 7: Potential Divider

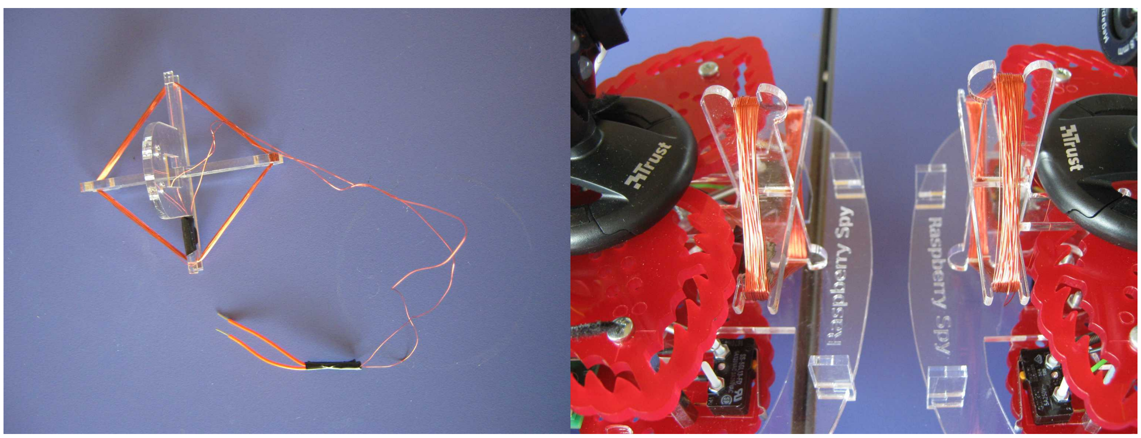

Figure 8: Example of Coil and mounting

The maximum distance between coils is around 70mm and a minimum distance is also sometimes observed.

A Circuit Diagrams

Figure 9 shows the whole schematic for the near-field receiver.

Figure 11 shows the prototype circuit on solderless breadboard using two MCP6283 single Op-Amp 8-pin DIPs.

Figure 10 shows the receiver circuit on the PCB (top half of picture) using a single dual Op-Amp MCP6282 SOIC package. The second (lower) chip is used as a buffer in the transmitter. In future board versions an MCP6284 quad Op-Amp could be used to reduce the part count.

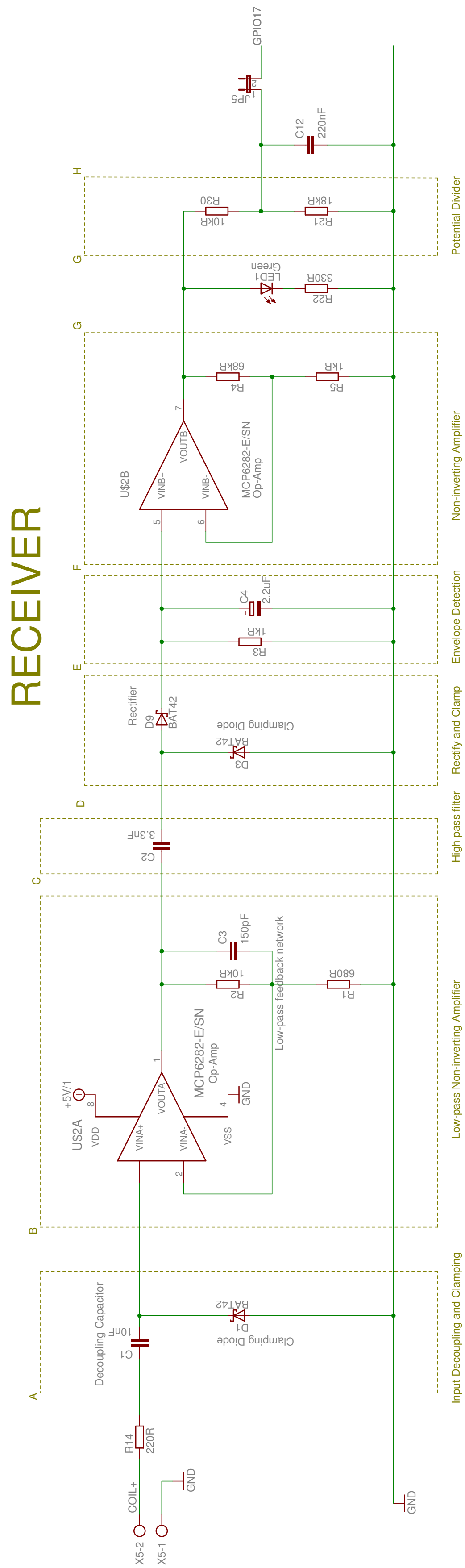

Figure 9: Whole Receiver Circuit

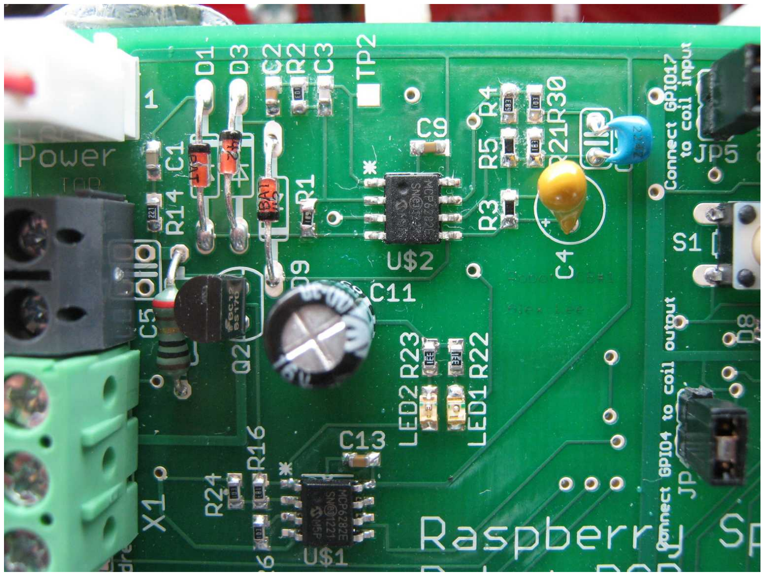

Figure 10: Receiving and Transmitting Circuits on PCB

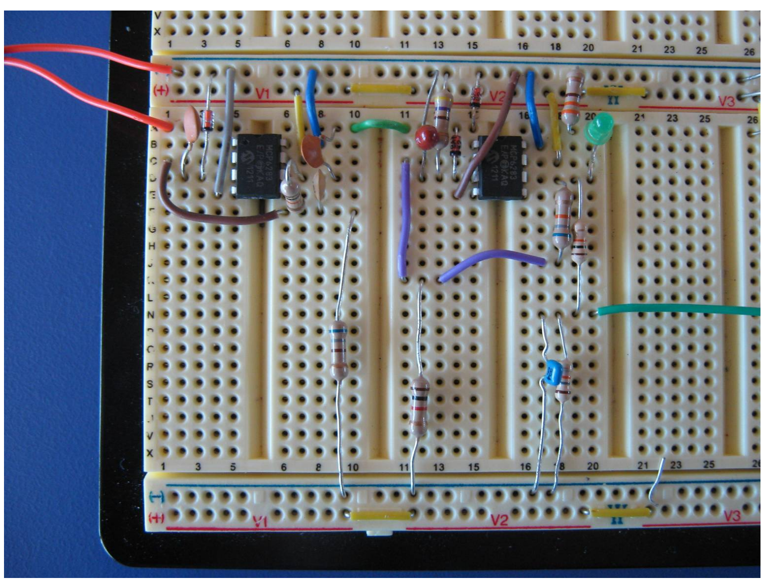

Figure 11: Receiving Circuit on Solderless Breadboard