ECE 342 Fall 2017 Optoelectronic Link Project

Lab 2: Active Bandpass Filters

Overview

The performance of any electronic circuit, analog or digital, is limited by the noise floor. In a classical system, the signal should be above the noise floor to be considered 'detectable'. The measure of signal strength vs. the average power of the noise floor is called the ***signal to noise ratio(SNR)***. The definition of a "detectable signal" varies from being 3 dB above the noise floor to 10 dB above the noise floor. In modern systems in which coding is used, the signal can actually be below the noise floor by several dB, but still be detected using correlation.

The frequency bandwidth of the signal is a major factor in determining the noise floor. Ideally, the signal and the receiver should have an infinitesimally small bandwidth, so that noise is eliminated. However, a practical system will have a finite bandwidth, and the frequency bandwidth of the receiver must be large enough to tolerate both fabrication tolerances and operating condition variations such as temperature, supply voltage, etc.

Based on the LED and photodiode data, the photodiode's peak output current will be less than 1.5 nA at a distance of 50', which is the minimum transmission range specification for the optical link. Thus, based on the TZA specifications of Task 1, the signal strength at the TZA output will be less than 100 μV, below the detection limit of both the oscilloscopes in the Al Whitney Lab and your Digilent Analog Discovery units. This signal must be amplified to a measurable level.

Any amplification process in the signal chain will amplify both the signal and the noise in the system, as well add noise of its own. Thus, the signal-to-noise ratio will actually degrade as the signal goes through the amplifier chain! Therefore, the noise floor of the optical link will be determined primarily be the first stage, the transimpedance amplifier of Task 1. However, the following amplifier(s) can further limit the bandwidth of the measurement, and hence improve the SNR.

An ***active filter*** is a filter circuit which includes an amplifier as well as the traditional passive components (R,C, rarely L) you studied in ECE 210 and ECE 214. In this task, you will design a ***multiple feedback bandpass filter*** to simultaneously amplify and filter the TZA output.

Determining the Noise Floor

The noise floor of the optical link will be determined primarily be the first stage, the transimpedance amplifier of Task 1. Two primary components of the noise current will be the contributions from the photodiode and the feedback resistor.

The rms noise current due to the photodiode is given by:

$$I_{\text{noise,pd}} = \sqrt{2qI_{dark}\Delta f} \qquad \text{(Eq.1)}$$

where q is unit charge, I_{dark} is the "dark current" of the photodiode, and Δf is the bandwidth of the sampled signal. The dark current of a diode is the current measured when a bias voltage is applied and the diode is shielded from light, i.e. it is in the dark. In the TZA configuration, the photodiode is effectively connected between the v_+ and v_- terminals of the op-amp. As the voltage difference between these two terminals is approximately zero, the dark current should also be approximately zero. However, the background light will also generate a photoresponse, which can be inserted into Eq. 1 instead of the dark current. It should be noted that the background light is also noisy, so the actual noise current will be somewhat larger.

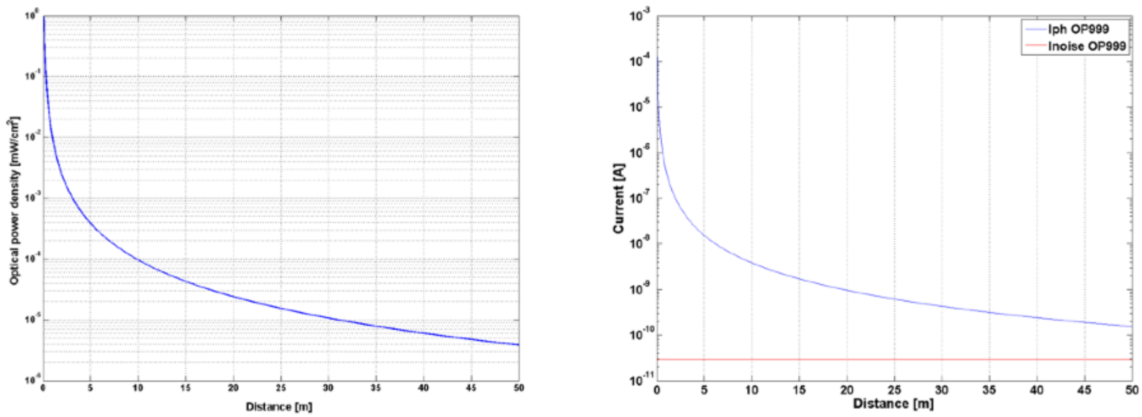
The noise current due to the feedback resistor of the TZA, known as Johnson noise, is given by:

$$I_{\text{noise,Rf}} = \sqrt{\frac{4k_B T\Delta f}{R}} \qquad \text{(Eq.2)}$$

where k_B is the Boltzmann constant (k_B = 1.38 x 10^{-23} J/K), T is the temperature in K, and R is the feedback resistor used to set the gain of the TZA. It should be noted that having a larger resistor will not only increase the gain for the signal, it will also reduce the noise contribution from the feedback resistor.

The Detection Limit

The maximum transmission distance for the optical link will be determined by the detection limit of the TZA. Figure 1(a) plots the optical power incident on a 1 cm^2 unit area as a function of distance from the transmitting LED. Figure 1(b) plots the peak photocurrent using the incident optical power and the OP999's responsivity, as well as the noise current calculated using (Eq.1) and (Eq.2).



(a) **(b)**

Figure 1. (a) Incident optical power per unit area, as a function of distance; **(b)** Photocurrent and noise current for the OP999 photodetector for f_0 = 20 kHz and Δf = 2 kHz.

The assumptions made in the calculations are that the background light generates a DC current of 60 nA, and the feedback resistor of the TZA is R = 39 kΩ. The signal frequency is f_0 = 20 kHz and the measurement bandwidth is Δf = 2 kHz. The signal current is approximately two orders of magnitude larger than the noise current at a distance of d = 15 m ≅ 50'. Based on figure 1(b), a well designed receiver should be able to detect the signal past a distance of d = 50 m = 165'!

The Multiple Feedback Bandpass Filter

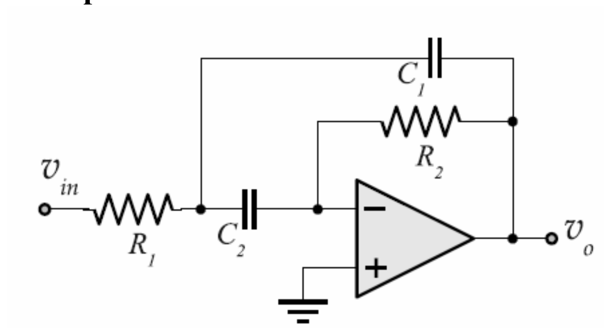


Figure 2. Multiple feedback bandpass active filter circuit

Figure 2 shows a "Multiple Feedback Bandpass" (MFBP) active filter. It provides one possible method of using a single op-amp to implement the generic 2nd order bandpass transfer function given by:

$$H(j\omega) = \frac{K\left(\frac{\omega_p}{Q_p}\right)(j\omega)}{(j\omega)^2 + \left(\frac{\omega_p}{Q_p}\right)(j\omega) + \omega_p^2} \qquad \text{(Eq. 3)}$$

The values ω_p and Q_p are called the "pole frequency" and the "pole Q" respectively. The bandpass characteristic $|H(j\omega)|$ is (roughly) centered at $\omega = \omega_p$, where the filter gain is $|H(j\omega)| = |K|$. Small values of Q_p result in very broad frequency responses about the center frequency, while larger values give sharp filter characteristics. As Q_p becomes large, the value of Q_p reflects the ratio of the center-frequency to the 3-dB bandwidth. For example, a 20 kHz 2nd order bandpass filter with 3-dB bandwidth 1 kHz would require $\omega_p \cong 2\pi(20\text{x}10^3)$ and $Q_p \cong 20$.

Higher order filters can be formed by cascading MFBP sections, where each section is dedicated to implementing a complex-conjugate pair of poles. For conjugate-pole locations of $p_i = \sigma \pm j\omega_0$, the resulting values of ω_p and Q_p are:

$$\omega_p = \sqrt{\sigma^2 + \omega_0^2} \qquad Q_p = \frac{1}{2}\sqrt{1 + \frac{\omega_0^2}{\sigma^2}} \qquad \text{(Eq. 4)}$$

Assuming ideal op-amp characteristics, the transfer function of the above active filter can shown to be:

$$\frac{v_{out}(j\omega)}{v_{in}(j\omega)} - \frac{-\left(\frac{1}{R_1C_1}\right)(j\omega)}{(j\omega)^2 + \left(\frac{1}{R_2C_1} + \frac{1}{R_2C_2}\right)(j\omega) + \frac{1}{R_1R_2C_1C_2}} \qquad \text{(Eq. 5)}$$

To ease component matching requirements, most designers select a single convenient capacitor value $C = C_1 = C_2$ (see mini tutorial #220 from Analog Devices, AD MT-220). The remaining components are selected to obtain the desired values of ω_p, Q_p and K. You'll find that for this circuit, the gain cannot be set independently from Q_p. In fact, using (Eq.3) and (Eq.5), $Q_p \propto \sqrt{|K|}$. The gain can be lowered by using a resistor divider on the input, as in the AD MT-220, but increasing the gain would require a second amplifier stage.

Task 2 Specifications and Design Constraints

In this task, you will design an active bandpass filter using the MFBF topology. The specifications and constraints are given in table 1.

Table 1. Specifications and constraints for the Active Bandpass Filter module

Filter Topology	Multiple feedback bandpass filter
Center frequency	20 kHz
3 dB bandwidth	Large enough to accommodate the ±5% tolerance on transmitter frequency
Gain	1,000 V/V or larger
Power supplies	± 12 V
Op-Amp	LF347 quad op-amp. Another op-amp may be used pending instructor approval if a good justification is given.

Tasks

1. ***Active Bandpass Filter Design:*** Design an active bandpass filter as specified in Table 1. Choose the Q to achieve the necessary bandwidth to accommodate the ±5% tolerance on your clock frequency. The relationships among K, ω_p, Q, R_1, R_2, C_1 and C_2 have been derived and posted for your reference on BlackBoard. The filter gain K and quality factor Q (therefore its 3 dB bandwidth) are related and cannot be set independently.

2. ***Simulation:*** Use a simulation to determine the frequency response of the active bandpass filter. Be sure to accurately show the frequency region near f_0.

3. ***Active Bandpass Filter Construction and Testing:*** Build the active bandpass filter. Measure its gain from 100 Hz to 1 MHz using the network analyzer function on the Analog Discovery. Determine the actual center frequency, bandwidth and gain of your filter. Adjust your component values until you meet your specifications.

4. ***Report and Demonstration:***
   - Your *full* report should clearly describe your design process, and present your theoretical, simulated, and experimental results. All lab partners should collaborate in the writing of the report.
   - Your *draft report* should be submitted to your TA electronically as a PDF file by Monday, 16 October 2017 at 2:00 PM. The TA will comment on your report by Wednesday, 18 October 2017 at 2:00 PM.
   - The *final report* for this task should be submitted to your TA electronically as a PDF file by Friday, 20 October 2017 at 2:00 PM. Make sure that you make necessary corrections as indicated by Prof. Payne as well as the TAs.
   - You'll be asked to schedule a short demonstration of your amplifier in the week of the due date. Each lab partner will be asked to reproduce a measurement from the report, and show where the measurement and measurement technique was recorded in their lab notebook. (Lab partners each receive a separate grade.)

Hints and tips:

1. Pay attention to the gain-bandwidth limitation of the LF 347 op-amp, and the gain-quality factor relation. Can you implement this filter with a single MFBF stage?
2. If you use two or more stages, do they need to have identical center frequencies?
3. When simulating your filter, the final load should be a 1 MΩ resistance in parallel with a 22 pF capacitor, modeling the input characteristic of the Digilent Analog Discovery. The input resistance of the common-source amplifier which will follow your filter will also be 1 MΩ.
4. Look at the output voltage swing vs. output load and output impedance vs. frequency plots of the LF347 (or other op-amp that you are using). Keep in mind the TZA is an op-amp circuit driving the input of your active bandpass filter. Does it make sense to choose $R_1 \leq 1$ kΩ?
5. Follow the procedure in the Amplifier Characterization document posted on BlackBoard. Before you do any small-signal measurements, ground the input of your active bandpass filter and look at the output with an oscilloscope. Is the output zero, as you would expect, or something else? If it is as you expected, then apply a 20 kHz signal with the AWG and then turn it off. Is the output zero after you turn off the signal, as you would expect, or something else?
6. **When measuring the gain**: You need a gain that is larger than 1,000 V/V. The input signal should probably have a peak magnitude of 10 mV or less. Unfortunately, the Analog Discovery's 500 μV/bit resolution means that the resulting sine wave has a lot of harmonics, and the frequency response measurement will be very noisy. Instead, use a voltage divider at the AWG output (e.g. 1 kΩ – 10 Ω) and set the AWG output magnitude to 100 mV peak. You will get a

cleaner frequency response. Don't forget to factor in the loss of the voltage divider. i.e. if you measured a gain of only 24 dB, and the voltage divider loss is 40 dB, the actual filter gain is 24 + 40 = 64 dB.

7. A *test case* document has been provided to you on BlackBoard. A test case is a standardized document where a device/circuit/system designer provides fabrication engineers and quality control engineers with the necessary information to verify that the product works as designed.

Time Management and Lab Notebook Documentation
ECE 342 Fall 2016 Lab 2

Group #___________ Names:_____________________________

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The deadlines for Task 2 are given below. In unusual circumstances, you may request a change of one or more of the deadlines listed below. This request must be approved either Monday or Tuesday of the week in which the lab is assigned.

If a change in schedule is approved, have the instructor/TA change and initial the dates listed below, and sign here:

22 September	**Watch the lab briefing and review the deadlines given below**. Any modifications must be approved by Wednesday, 4:00p.m.
Thursday 28 September 4:50 PM	***(10 pts)*** **Circuit design and simulation results completed.** All designs must be entered into lab notebooks *TA's: Rate from 1(worst) to 5 (best)...* Clarity of Design Process: 1 2 3 4 5 Lab Notebook Procedures: 1 2 3 4 5 Simulations Completed: 1 2 3 4 5 Clarity of Simulation Results: 1 2 3 4 5 Successful Design Complete: 1 2 3 4 5 Early Check-off: 1 2 3 4 5 Signature: Date:
Thursday 12 October 4:50 PM	***(10 pts)*** **Experimental measurements completed and entered into lab notebooks.** *TA's: Rate from 1(worst) to 5 (best)...* Experimental Procedures Clearly Described: 1 2 3 4 5 Lab Notebook Procedures: 1 2 3 4 5 Preliminary Analysis of Results: 1 2 3 4 5 Clarity of Results Presentation: 1 2 3 4 5 Successful Design Demonstrated: 1 2 3 4 5 Early Check-Off: 1 2 3 4 5 Signature: Date:
Monday 16 October 2:00 PM	***(10 pts)*** **Rough draft of report submitted by 2:00 PM**. Text should be complete, requiring editing primarily for grammar, consistency, or presentation Signature: Date:
As Scheduled:	***(30 pts)*** **Demonstration:** Reproduce a measurement from your report for a grader. Expect to show the grader where the requested measurement and measurement technique was recorded in your notebook.
Friday 20 October 2:00 PM	***(40 pts)*** **Final Report Due by 2:00 PM.** Turn in your final report with this form. Reports are not accepted late.