ECE 342 Optical Link Project

LAB 2: ACTIVE BANDPASS FILTERS MODULE

Function in the Optical Link Project

- The second stage in the receiver will amplify the signal while limiting the effect of noise
- This is accomplished by using a narrow bandwidth filter
- The 3 dB bandwidth of the bandpass filter should be large enough to accommodate the ±5% tolerance of the clock frequency
- This will be accomplished by using one or more stages of the Multiple Feedback Bandpass Filter (MFBF)

Noise Sources in the Optical Link

- Electronic noise comes in two flavors:
  - Random fluctuations in voltage / current due to the quantum mechanical (i.e. statistical) nature of electronic devices (including resistors, capacitors and inductors)
  - Interfering signals, i.e. other signals
- To reduce interfering signals, use a highly selective bandpass filter
- It turns out this will reduce the other type of noise as well

Types of Electronics Noise

- Photodetector: ***Shot*** noise (& all others below for transistors)
- Resistors: ***Thermal***, a.k.a. ***Johnson***, noise
- Transistors & op-amps:
  - ***Shot*** noise, due to carrier injection through a pn junction
  - ***Generation-recombination*** noise, due to the statistical nature of the generation & recombination of carriers in semiconductors
  - ***1/f*** noise, usually associated with material failure / imperfection in fabrication
  - ***1/f²*** noise, usually associated with metal-semiconductor contacts

For a relatively straightforward description of noise types in semiconductor devices: http://www.eng.auburn.edu/~wilambm/pap/2011/K10147_C011.pdf

Noise Sources Limiting the Receiver

- In a well designed receiver (optical, RF, cable etc.) the first stage will set the noise floor *You will encounter "not well-designed" in Task 5*
- Every following amplifier stage will add its own noise in addition to amplifying the signal and noise from the previous stage
- Thus the signal-to-noise ratio (SNR) will get ***worse!***
- The first stage (TZA) should have the smallest possible noise figure
- To understand how to achieve this, and how to limit the effect of noise on the receiver, we need to understand the photodetector shot noise and the resistor thermal noise

Shot Noise in the Photodiode

- The shot noise in the photodiode is given by:

$$I_{noise,pd} = \sqrt{2qI_{dark}\Delta f}$$

- The dark current I_{dark} is the current of the photodiode with no light incident on the device
  - I_{dark} should be zero for the TZA configuration, as there is no bias across the diode
  - But the photodiode detects the background light, which generates a photocurrent that behaves like I_{dark}
  - If you build an optical link, use optics to limit your noise signal
- The measurement bandwidth Δf is another limiting factor
  - Use high-Q, i.e. narrow bandwidth, bandpass filters to limit the noise

Thermal Noise in the TZA Resistor

- Thermal noise is due to the random motion of atoms & electrons in the resistor caused by their thermal energy
- Thermal, a.k.a. Johnson, noise of a resistor is given by

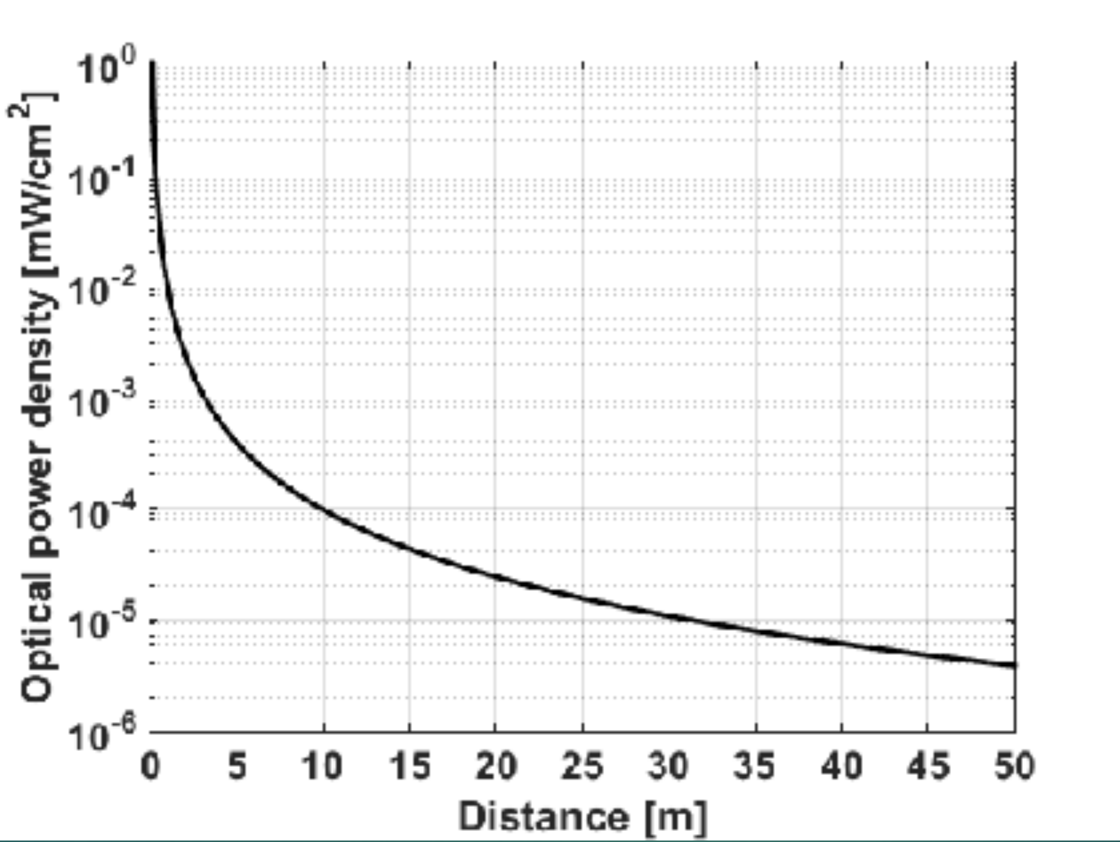
$$I_{noise,R} = \sqrt{\frac{4k_B T\Delta f}{R}}$$

- Inversely proportional to $\sqrt{R}$, so make the feedback resistor R_F in the TZA as large as possible
- Also proportional to $\sqrt{\Delta f}$, so limit measurement bandwidth

Optical Link (Power) Budget

- Any communications system (including radar & ladar) has a link budget
  - This is in terms of available power, not $$$
- Calculate how much power is transmitted
- Calculate how the power drops with distance
  - e.g. Friis transmission formula from ECE 351
  - Power will drop with $1/R^2$
  - The power density will drop by a factor 100 for a 10x increase in R!
- We can then determine required gain at the receiver to obtain the desired signal levels

Power Density vs. Distance R

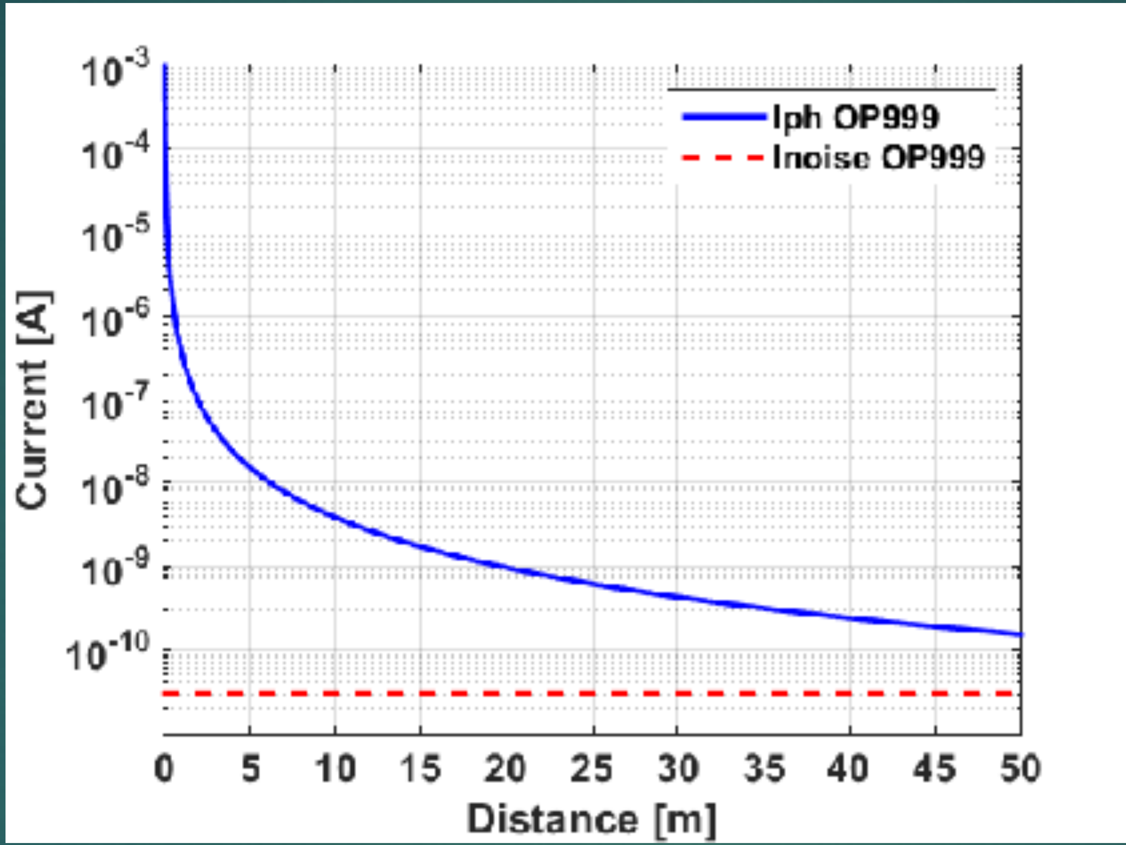


Power density vs. transmission distance for the SIR 563st3f IR LED
LED output power = 8.4 mW for experimental conditions, as measured by N. Emanetoglu using an OceanOptics RedTide spectrometer with an OceanOptics integrating sphere
Trust but verify…

Limit of Detection for the Optical Link

- The limit of detection (LOD) is set by the noise floor of the receiver
- The signal current can be calculated using:
  - The OP-999 photodiode sensitivity
  - Signal frequency of 20 kHz (large enough to avoid $1/f$ & $1/f^2$)
  - Signal bandwidth of 2 kHz
  - TZA gain 39 kΩ
    - less than your limit due to the compensation capacitor size
  - Optical power density vs. distance given in the previous slide
  - A background current of 10 nA (a lot!) assumed for the PD

PD Photocurrent vs. Distance R



Noise current ~ 30 pA for R_F = 39 kΩ, and ~ 21 pA for R_F = 82 kΩ

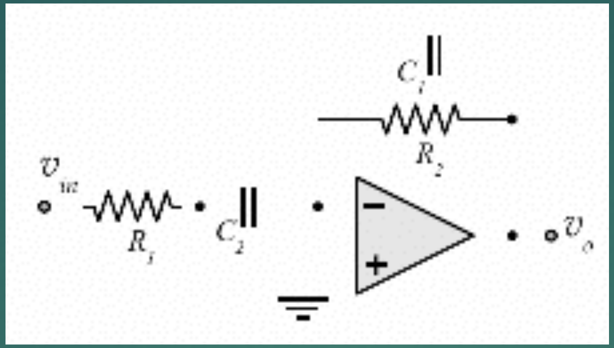
Photocurrent should be at least 20 dB above noise floor even at 50 m / 165 ft for a well designed system

This figure only accounts for the receiver's 3 dB bandwidth, nothing about receiver gain

Calculating the Required Gain

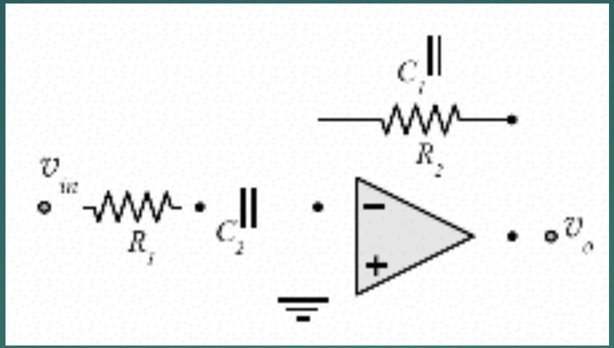
- The PD photocurrent should be ~ 1.7 nA @ 50’ (15.15 m) if the LED and PD are aligned and working as specified
- TZA output < 170 μV rms @ 50’
- Need a 5V digital signal at the output (or as close to it as possible) *Note:* this is ideally. You are held to a specification of 6 dB SNR @ 50’ as calculated by the Digilent’s spectrum analyzer.
- Overall voltage gain of the receiver stages following the TZA needs to be ~ 83 dB
- These stages also need to limit the 3 dB bandwidth to improve the signal-to-noise ratio
  - Ideally the 3 dB bandwidth $\Delta f = 0$!
  - Need ~ 2 kHz to account for the clock frequency tolerance

Multiple Feedback Bandpass Filter



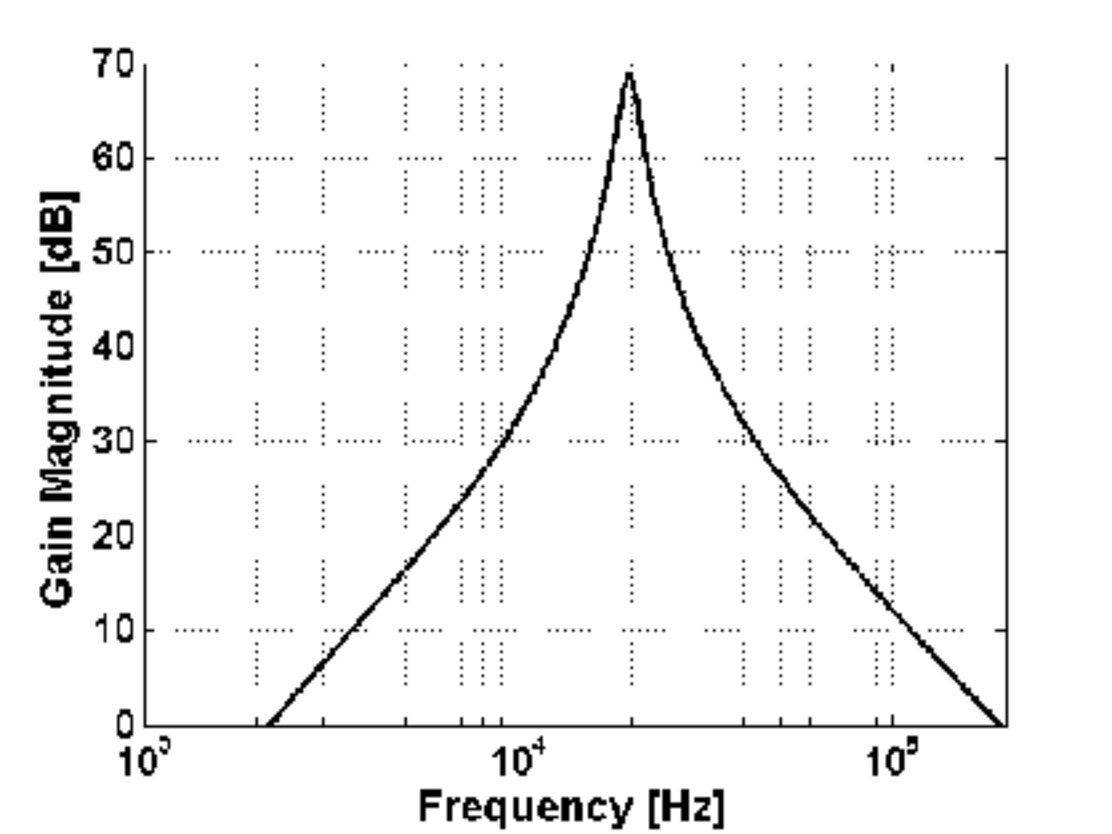
- Amplifies signal while bandpass filtering it
- Gain K and quality factor Q are related
  - High K = High Q = narrow Δf
- Quality factor of a bandpass filter is defined as: $Q = \frac{f_c}{\Delta f}$
- Design equations given in lab manual, MT-220 mini-tutorial from Analog Devices and my hand written notes posted on BlackBoard

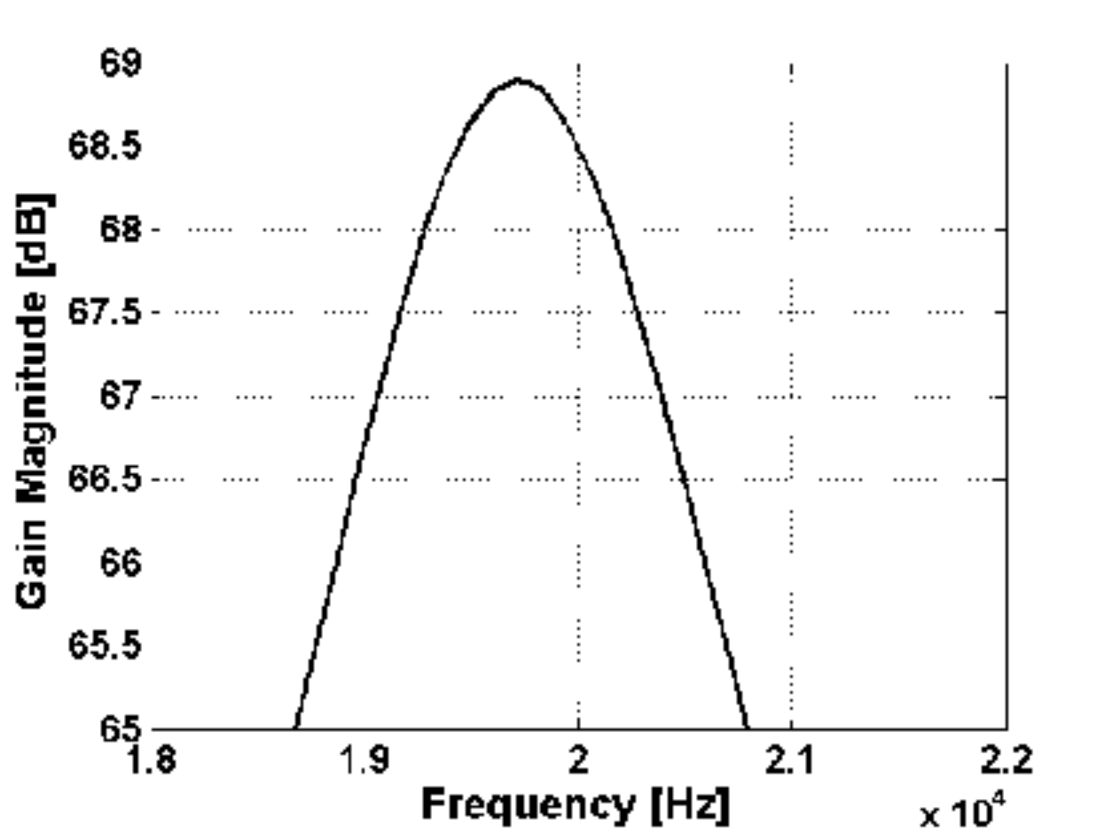
MFBF Design Procedure



- Need to achieve an overall gain of 1,000 V/V or larger @ 20 kHz in the filter stage
  - Will use a final amplifier with a gain > 10 V/V afterwards
- Can this be done with a single op-amp (LF347) ?
- Choose $C_1 = C_2$ for convenience
- Calculate R_1 and R_2 from the design equations
  - $R_1 \geq 1\ k\Omega$ to avoid problems with the op-amp's output resistance and current drive capability

My MFBF Results





- Peak gain close to 69 dB
- 3 dB bandwidth is 1960 Hz

MFBF Test Case Document

- A detailed, step-by-step test & measurement guide has been provided on the course website
- Follow the steps
- Read the two test notes to understand some of the problems you may / will encounter

Measuring the Gain of the MFBF (1)

- The Digilent has a 500 μV resolution limit
  - Any signal < 2 mV is essentially a square wave
  - Any signal < 5 mV is too distorted to analyze accurately
- Use a 100:1 or 1000:1 voltage divider to make the input small
  - Ideally 100 Ω: 1Ω, but the Digilent AWG can’t drive it well
  - Make sure $R_1 + R_2 > 500\ \Omega$
  - Use a 100 mV or 1 V amplitude signal
- Measure the voltage divider’s insertion loss, factor it in to your final gain calculation
  - Connect AWG1 & OSC1 to the divider’s input
  - Connect OSC2 to the divider’s output

Measuring the Gain of the MFBF (2)

- Measure the active filter's gain, factor in the voltage divider afterwards
  - Connect AWG1 & OSC1 to the divider's input
  - Connect OSC2 to the active filter's output
- Partition the measurement into three frequency ranges
  - Assuming a 1000:1 voltage divider
  - 1 kHz – 10 kHz and 30 kHz to 200 kHz for the low gain
  - 10 kHz – 30 kHz for the high gain region
  - Set max_gain parameter to 0.1x for the low gain (or 0.01x)
  - Set max_gain to 20x for the high gain region
  - Export each measurement as a .CSV file, stich in Excel, Matlab, etc.

Tips and Tricks (1)

- If you use two (or more) MFBF stages, do their center frequencies need to be identical?
  - Check out Fig. 17.49 and associated text
- Follow the procedure outlined in the document AmplifierCharacterization.pdf on BlackBoard
  - Use the scope and waveform generator to make sure that:
    - the input signal is small enough so that the output isn't clipping
    - the output offset isn't causing the amplifier to rail
  - Then use the network analyzer mode to measure gain

Tips & Tricks (2)

- The Digilent's power rails and AWG outputs are very noisy
  - You might be surprised to discover a rail-to-rail output if you connect the AWG to the input without the voltage divider
  - There can be a 5-10 mV noise on the AWG
- Power supply rejection
  - The wires and breadboard connectors aren't 0 Ω
  - The current draw can cause ripples on the order of 1-10 μV
  - The LF347's power supply rejection ratio at 20 kHz is only 40 dB
  - So this ripple will be amplified by at least 20 dB (~ 30 dB for my sample), pulling in more current, causing an oscillation!
  - May need bypass capacitors at both supply pins to eliminate oscillation

Some References

- Sources of noise in electronics devices: http://www.eng.auburn.edu/~wilambm/pap/2011/K10147_C011.pdf
- TI tutorial on noise figure of op-amps: http://www.ti.com/lit/an/slyt094/slyt094.pdf
- Agilent (now Keysight) application note on noise figure measurements: http://cp.literature.agilent.com/litweb/pdf/5952-8255E.pdf
- IEEE MTTS tutorial on receiver noise: http://www.ieee.li/pdf/viewgraphs_mohr_noise.pdf
- Photodiode noise:

  http://users.ox.ac.uk/~atdgroup/technicalnotes/Getting%20the%20best%20out%20of%20photodiode%20detectors.pdf

  Very comprehensive report by D. Kleinfeld, 1979: https://physics.ucsd.edu/neurophysics/lab/DK_Photodetector_Noise.pdf