ECE137b Second Design Project Option

revision 5/24/2023

You must purchase lead-free solder from the electronics shop. Do not purchase solder elsewhere, as it will likely be tin/lead solder, which is toxic. "Solder-sucker" desoldering tools are not permitted in the lab, as they disperse a dust of solder granules into the air and onto surrounding surfaces. If you are also foolishly using tin/lead solder, you will then poison yourself. Again, use lead-free solder from the shop, and use desoldering wick to remove solder. ***Projects assembled using lead-containing solder will receive a grade of zero***.

General Comments

You have a choice of doing one of three design projects, a fiber optic link, a switched mode power amplifier, or an acoustic phased array. All are intended to be
-Representative of real applications, incorporating aspects of both circuit and system design.
- Highly independent in character. It is strongly expected that there should be minimal similarity between projects designed by different groups.
-A significant fraction of the class grade and hence a significant time commitment

You will be working in groups of 2.

Construction Hints

These are high frequency circuits. Construction on a proto-board is of value for DC testing and for AC functional testing at signal frequency well below that of the real design. Functional high speed operation will require a soldered design with tight physical construction practices. Construction on a circuit board with a ground plane is very strongly recommended, as is signal wiring with adhesive copper tape. See the links on the web site for information on construction practices.

Lab Project Option #2: Fiber Optic Link

Background

data pattern generation

You will be building an optical data transmission link. This will consist of a pseudo random data pattern generator, a transmitter, a length of fiber, a receiver, and a decision circuit.

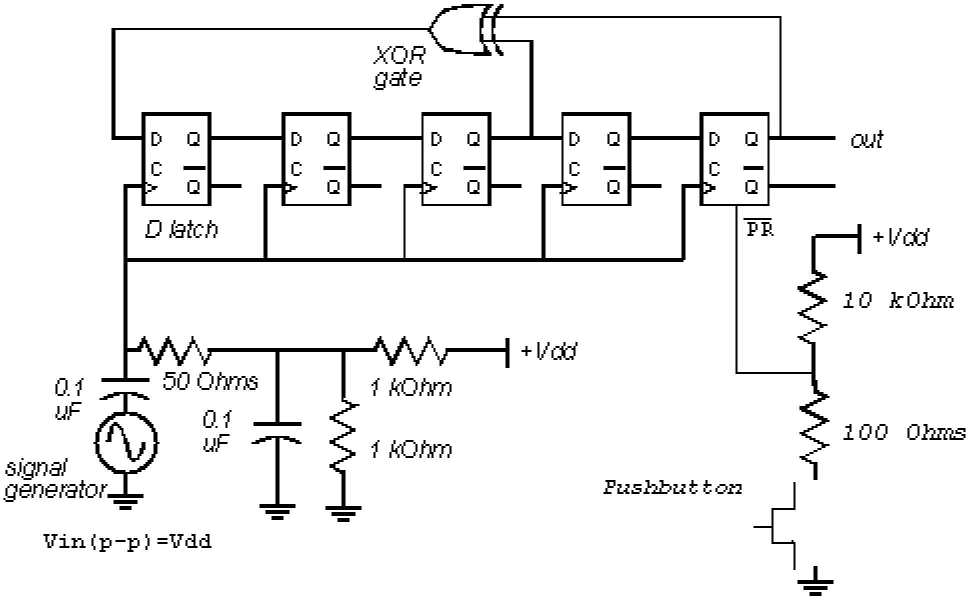

Figure 1: Pseudo-random sequence pulse generator

We need a pseudo random data pattern generator (Figure 1) to generate data patterns to test the link. A logic level diagram is as shown above. It can be easily constructed from standard digital logic parts. The 4000-series CMOS logic gates are too slow for your purposes here, limiting you to a maximum of ~2 MHz data rate. Instead, you must use the 74HC CMOS logic family, specifically the MM74HC74A. Dual D-type flip flop (the preset_bar and clear_bar inputs should be tied to logic high) and the MM74HC86 exclusive OR gate. The pushbutton circuit is necessary to initialize the circuit on power-up. You should use a normally open switch, so that the preset_bar is normally connected to Vdd.

There is some flexibility, but I suggest operating the ICs from a power supply between ground and Vdd= +5 Volts

Principles of pseudo random pattern generators are described in http://www.newwaveinstruments.com/resources/articles/m_sequence_linear_feedback_shift_register_lfsr.htm , and https://en.wikipedia.org/wiki/Linear-feedback_shift_register although it is not really necessary to read and understand this material.

Pattern generator to transmitter interface

You will build the data pattern generator and the transmitter on separate boards interconnected by a 50 Ohm coaxial cable interface. Figure 2 shows sketch of how do to this.

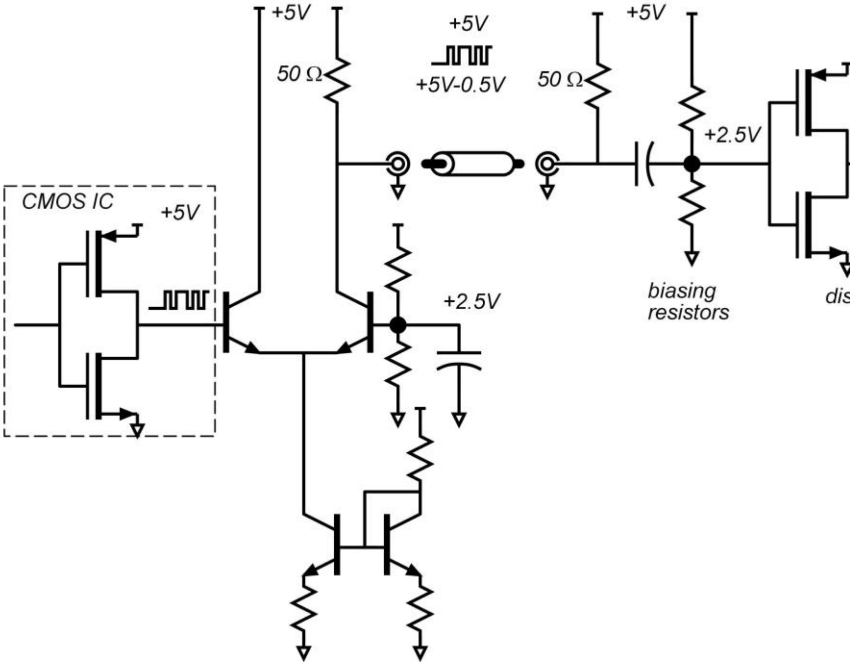

Figure 2: Digital driver stage for 50 Ohm coaxial cable.

I suggest that you design the coax cable driver to produce a 0.5Volt or 1.0 Volt peak-peak waveform, given the presence of a 50 Ohm external load. At the receiving end of the cable, a blocking capacitor and two biasing resistors shift the DC level to that required for the input to the transmitter.

Choice of optical components

The transmitter takes data and uses it to drive current into either an LED or a laser diode, which then generates light (optical power) in proportion to the drive current. The receiver uses a PIN photodiode to convert light back into an electrical current.

You have a choice of components, trading component cost against performance. Your grade, to the extent that it is based on circuit performance, will be based on circuit performance *relative* to the performance of the components you use, so don't pick the faster components simply in the hope of getting a better grade ! Instead, we are offering the faster components simply because the project might be more fun using them.

The lower-cost choice involves an LED source and an PIN photodiode detector, these coupled together with a very wide-diameter optical fiber. These components are specifically manufactured for the educational market.

The higher-cost, higher-performance choice involves a vertical-cavity laser (VCSEL) and a PIN photodiode detector, these coupled together with a 50 micron core, 125 micron cladding multimode optical fiber. These are standard components used by the data communications and telecommunications industries.

LED Transmitter

For this choice, you would use the IFE98 (slower) or ife91d (faster) light emitting diode for the transmitter, and your data will be coming direct from the data pattern generator above. The shop also has plastic optical fiber purchased from http://www.i-fiberoptics.com for connection of transmitter to receiver.

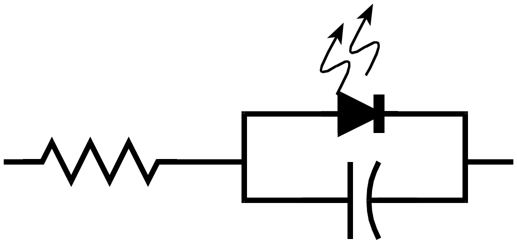

Figure 3: Approximate LED equivalent circuit, with ideal Is*exp(qV/kT) diode, parasitic diffusion capacitance, and parasitic series resistance

The objective is to convert the train of logic voltage pulses to a train of current pulses which drive the LED. The LED then coverts these into pulses of light. An approximate circuit model of an LED is as in Figure 3: an ideal diode in parallel with diffusion+depletion capacitance, and then some series resistance of perhaps 10-100 Ohms. Read the datasheet carefully: the internal RC time constant of the LED may be s*low* and you may have to *insert a zero* into the driver transfer function if you are to obtain acceptably fast optical waveforms. You will need to analyze the transient response of your network to correctly predict the pulse waveforms and understand the consequence of incorrectly setting the zero frequency.

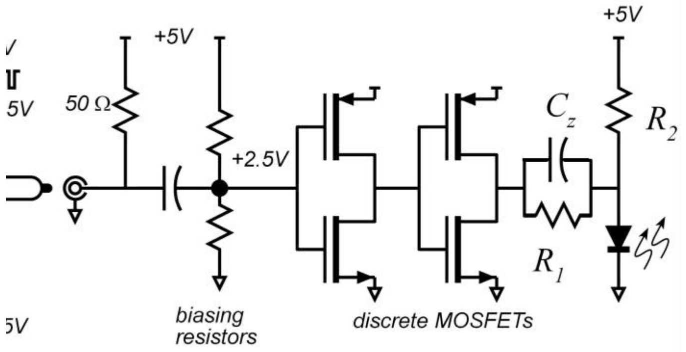

Figure 4: Suggested simplified diagram of the LED transmitter

Above is one sketch of how you might design the transmitter. *An integrated CMOS gate here is not allowed: you must use discrete MOSFETs so as to have you do the full circuit design.* In this circuit, the resistors R1 and R2 set the on-current *and* the off-state bias current of the LED, and the capacitor Cz introduces a zero which, if correctly selected, will speed up the optical switching waveforms without overshoot.

Not also, that by setting R1 and R2 appropriately, that the off-state (Boolean zero) current can be set to a nonzero value. This reduces the diode voltage swing and increases the transmitter speed.

Laser transmitter

For this choice, you would use a high speed laser diode. Again, for the transmitter, and your data will be coming direct from the data pattern generator. Most optical links use diode lasers: they are faster than LEDs, have a more nearly monochromatic optical spectrum (which leads to less pulse-spreading in the fiber) and, with a tightly unidirectional beam, couple light more easily into the narrow optical fiber core.

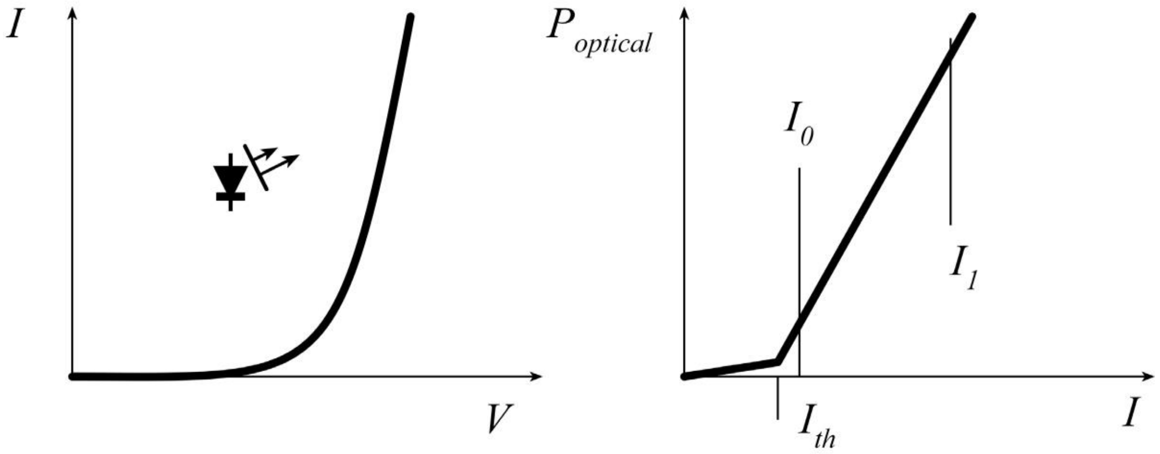

Figure 5: Laser DC current-voltage and power-current characteristics.

Figure 8 shows the laser DC current-voltage and power-current characteristics. The laser has the exponential I-V characteristics of any diode, except that the turn-on voltage is much larger than that of a common silicon diode. Check the data sheet. The optical output power, P_{out} vs DC current characteristics are shown on the right of the figure. Below I_{th} , the threshold current, the diode is not lasing. It has slow response and a wide optical spectrum. Above I_{th}, the diode is lasing. Above threshold, optical output power increases more steeply with current, the modulation response becomes fast, and the optical spectrum becomes more nearly monochromatic.

We therefore provide a small bias current I_0 when transmitting a zero and a larger current I_1 when transmitting a one. For many lasers, the threshold current is large and is highly variable. In that case the DC bias current I_0 is controlled by an op-amp negative feedback loop, with the laser optical output power measured by a built-in detector diode. Fortunately, for a VCSEL, at least for this lab project, the threshold current is sufficiently small that we can just provide a fixe bias current without using negative feedback.

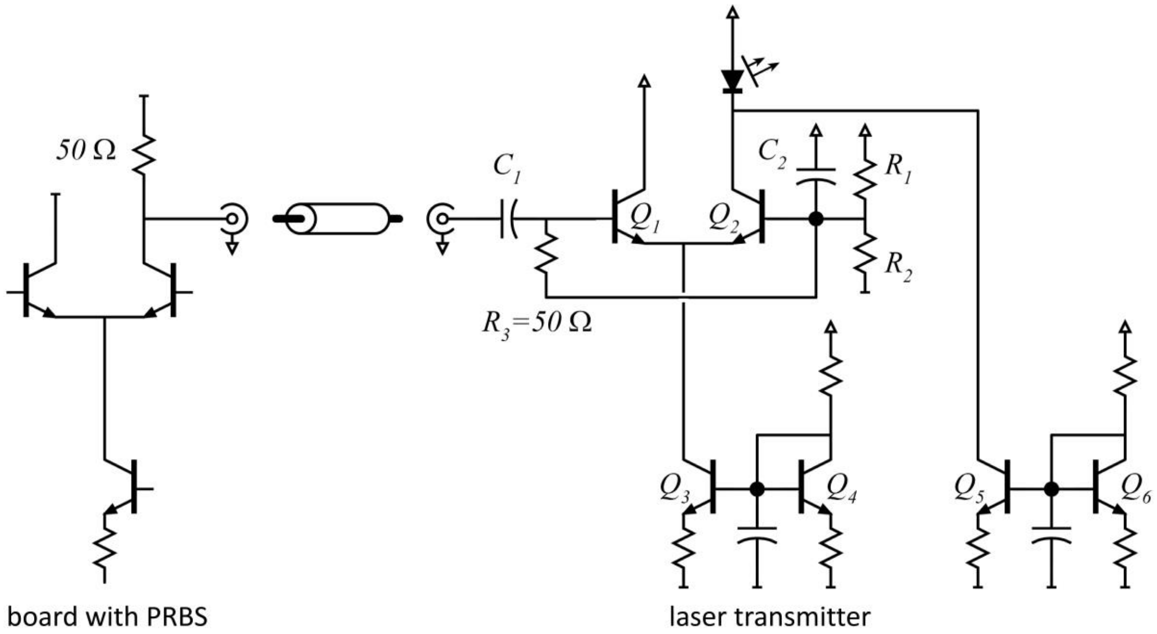

Figure 6: Example laser transmitter design

Figure 6 shows an example laser transmitter design. Perhaps you can come up with your own design. On the right of the diagram is the pulse driver stage from checkoff #1. This drives the 50 Ohm coaxial cable. The network C1, C2, R1, R2, R3 provides a 50 Ohm termination to the cable, plus provides DC bias to the bases of Q1 and Q2. These transistors, Q1 and Q2, switch the collector current of Q3 into the laser or dump it into ground. For an optical zero, the laser current is I_{C5} , while for an optical one, the laser current is $I_{C5}+I_{C3}$.

The laser diode is expensive, and is easily destroyed. Test your circuit with a RESISTOR IN PLACE OF THE LASER before you connect the laser. Generally be very careful. Make sure that your bypass capacitors don't introduce a sudden large spike of laser current when you power up your circuit. The circuit of Figure 7 will destroy the laser. Can you tell why ?

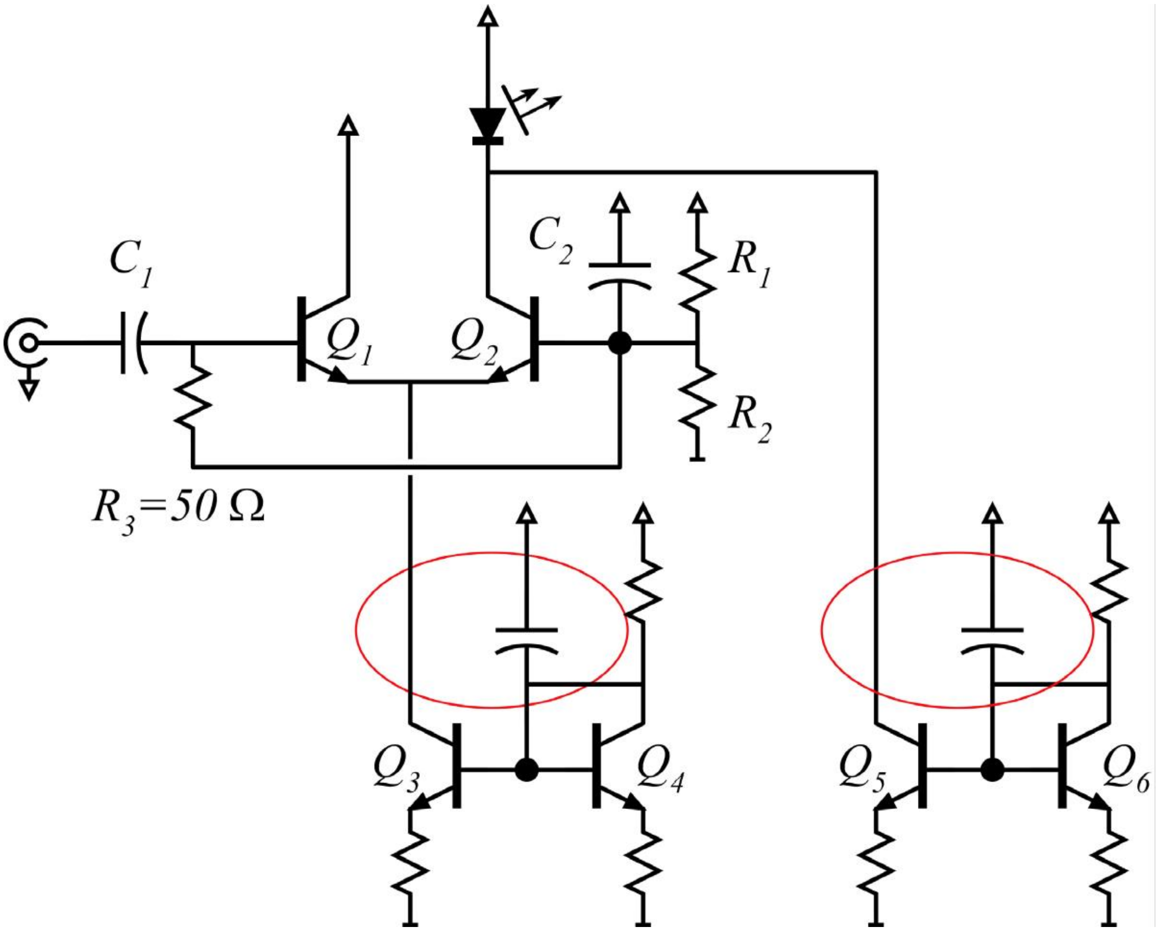

Figure 7: Circuit with badly-conceived DC biasing. This will destroy the laser upon circuit power-up

The laser is very fast, so circuit speed will be limited by wiring parasitics if your wiring is sloppy. It is best to use a ground plane for the power supply and -5V for the DC supply. The diode laser should be connected directly to the ground plane, and the wire lengths should be extremely short.

You should calculate the circuit switching times using the charge control method.

Optical detector for transmitter testing

You will also need an instrument to measure optical waveforms. This is shown below: connect a photodiode to a supply voltage through an ammeter. Bypass the diode anode with a capacitor. Add a 50 Ohm load on the board and a coax connector. Build it all very tight: no wires longer than 1/2 inch (absolute maximum). You can provide a 50 Ohm termination at the oscilloscope input, as shown. This will help further suppress pulse reflections and waveform distortion on the coaxial cable, but if you have a sending end 50 Ohm resistor on the photodiode, the 50 Ohm oscilloscope termination is not strictly necessary. You will get a bigger signal, and better signal/noise ratio, if you don't use the oscilloscope 50 Ohm termination.

As always, construction with a functional ground plane will help control wiring parasitics. The signal level from this detector will be small, and you will likely need to use signal averaging on the oscilloscope to obtain clean measurements.

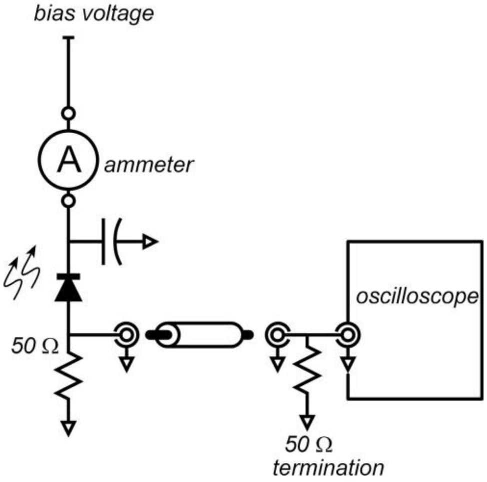

Figure 8: Optical receiver for waveform measurements

The receiver

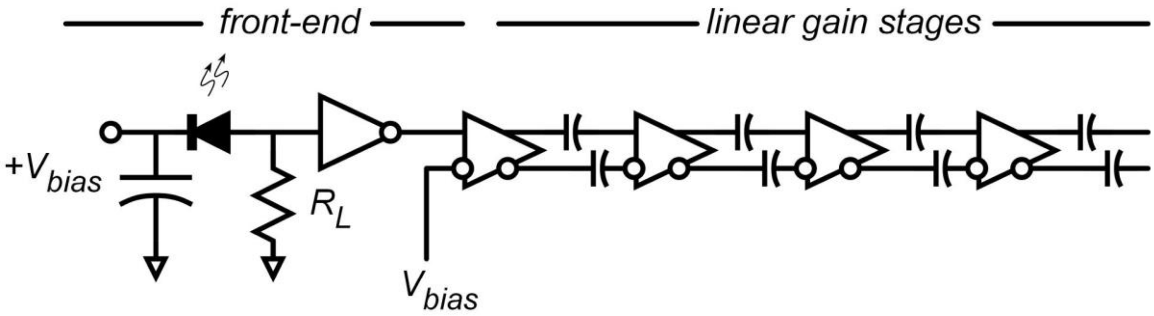

Figure 9: Simple optical receiver (not allowed; just for discussion).

Figure 9 shows a simple receiver. In this receiver, the data pattern is first converted back to electrical current using a reverse-biased diode: a photodiode. As noted earlier, the photodiode must be compatible with the laser or photodetector you are using, as must be the optical fiber.. This current is then converted into a voltage by passing through a load resistor RL and then amplified with the front-end stage.

Because of both the photodiode capacitance and the amplifier input capacitance, large values of load resistance will result in small bandwidth. A time constant analysis is imperative. Very low load resistances will however result in high levels of *noise*; **for this reason the load resistance in your design must not be less than 1 kOhms.**

Substantial gain is required after the preamplifier. Even with a few meters transmission distance in the fiber, losses in coupling into and out of the fiber are such that the photocurrent in this case is only ~20 microamps. One would like the receiver to function perhaps up to 10:1 additional optical loss (due to a long fiber in a real application). This then corresponds to 2 microamps photocurrent. We will assume that the decision circuits connected to the output of your receiver would need a 250 mV peak-peak signal to function. If the load resistance were 1000 Ohms, then a 2 microamp peak-peak photocurrent would produce 2 mVpp signal voltage on RL, and an additional 125:1 voltage gain would be required from the linear gain stages.

The amplifier chain must not be DC coupled, both because the photodiode signal is unipolar, not bipolar, and because of the high gains required will result in loss of control of the DC bias. AC coupling is instead required; in order for this to not interfere with data transmission, the low-frequency cutoff must be below 1/10,000 of the data rate. Hence for 10 Mb/s, the low-frequency cutoff must be below 1 kHz.

For the receiver to function with a strong input signal, as well as a weak one, the amplifier must also amplify correctly when driven with signals strong enough to drive it into limiting (clipping). This forces use of differential circuits, with the circuit designed so that that both the positive and negative clipping limits are set by cutoff, not saturation.

There are several major difficulties with the circuit of Figure 9. The first difficulty is the size of the DC blocking capacitors. For high speed, the load resistances of your gain stages will likely not be very large, and large capacitor values would be needed to obtain the necessary ~1kHz low-frequency cutoff.

A second difficulty is DC level design of the interface between the 1st and 2nd stages. If the first stage is not differential and the 2nd and subsequent stages are, then one will find it difficult to match the DC output of the front-end amplifier with Vbias, the voltage applied to the inverting (negative) input of the next stage.

A third difficulty is the tradeoff between receiver sensitivity and noise. If RL is large, there will be a large RC time constant resulting from the capacitance of the photodiode and the transistor input. If RL is small, the input-referred noise current from RL will be high, and the receiver will not be sensitive, and will not work with small input signals. To address this, you will use a standard ***transimpedance input stage.***

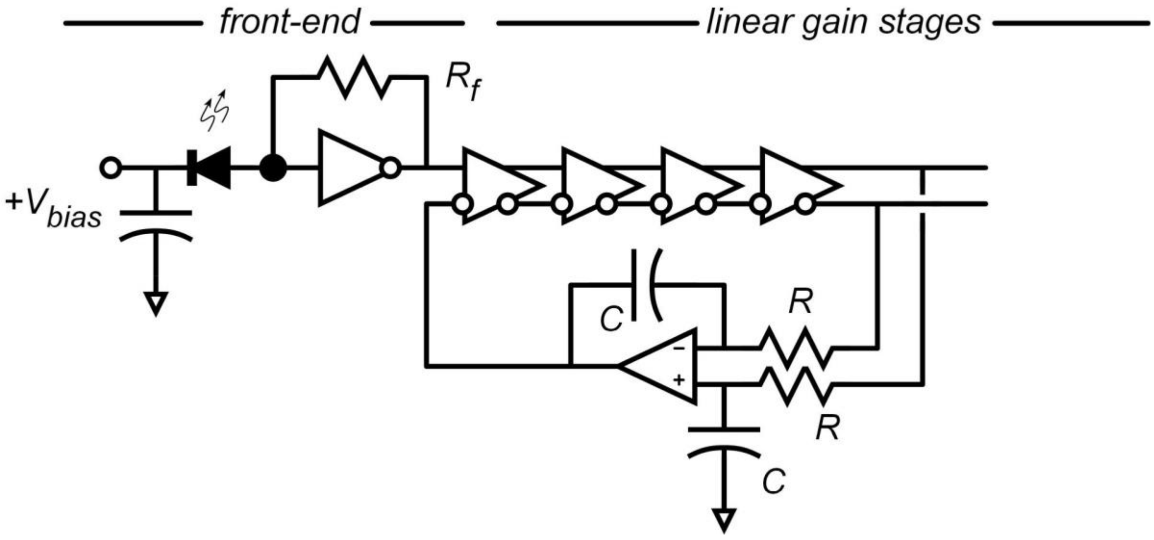

Figure 10: Optical receiver with (a) transimpedance front-end and (b) DC negative feedback.

For these reasons, modern optical receivers are more often in the general form of Figure 10. There are two significant differences between this structure and the design of Figure 9. First, a *transimpedance* input stage is used. This allows use of a large (~1 KOhm) feedback resistance for low noise, but still provides a small stage input impedance and hence a small RC charging time for the parallel combination of photodiode and transistor input capacitance.

The second feature is the negative feedback loop for DC restoration (Figure 10). Using the op-amp, as indicated, the differential DC output voltage is measured, and is used to set the input DC level to the linear gain stages. This forces the differential DC output voltage to zero, serving the same function as DC blocking capacitors in the forward signal patch. ***You must analyze the low-frequency response of this circuit quite carefully to determine the values of R and C needed for a given low-frequency cutoff***. Please feel free to use a commercial integrated op-amp for the DC negative feedback. *Note that the supply voltages needed for the op-amp may be quite different from the other parts of your circuit.* ***Consider the use of the ALD1702, as this can work with a +/- 2.5V or +/- 3.3V supply.***

Example circuits

Below are shown a few examples without detailed discussion. You can mix and match among these. Or, invent your own. You might consider whether emitter followers help gain-bandwidth products. Do cascode stages help ? There are many possibilities.

Some hints:
1) cascode stages tend to help bandwidth if the gain per stage is large, but otherwise tend to not help.

2) Adding emitter-follower buffers to the inputs of common-emitter differential stages tends to help bandwidth because the impedances presented to Cbe and Ccb of the differential common-emitter stage are reduced.

3) Using lower gain per stage and more stages tends to give more bandwidth than using fewer stages and higher gain per stage.

4) ***In all cases, analysis and math is your friend. An hour of math at your desk can save 10 hours of debugging in the lab.*** Please study the notes set showing MOTC bandwidth analysis of a differential pair with emitter-follower input buffers. Please consider the homework set that had a problem on MOTC bandwidth analysis of transimpedance stages.

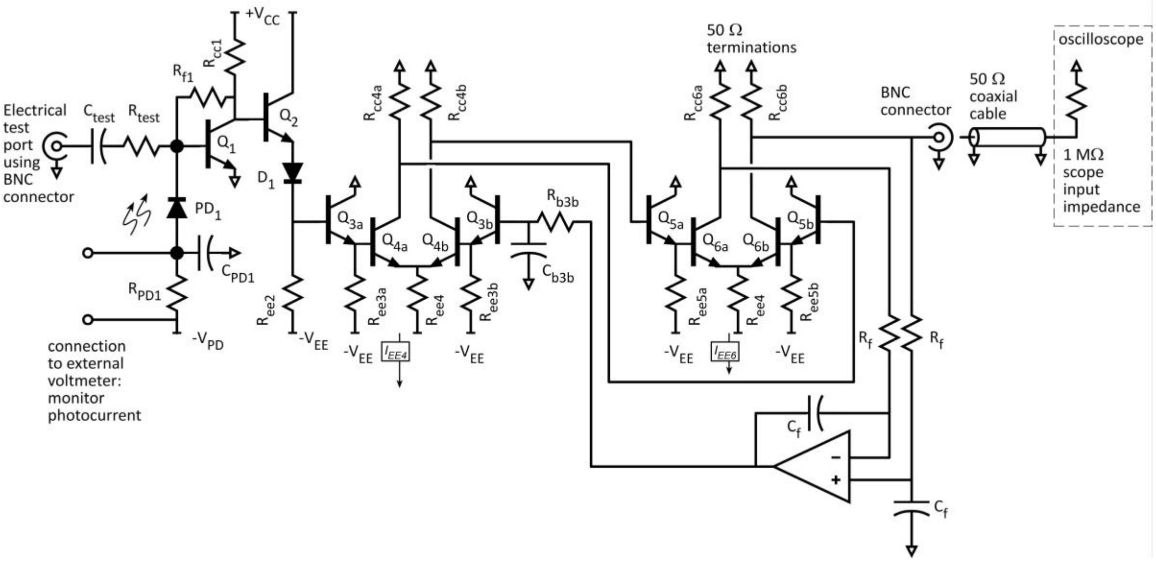

Figure 11: Example showing NPN TIA and all-NPN differential gain blocks. R_{F1}=1 kΩ, R_{test}=100 kΩ, C_{test}=10 nF, R_{b3b}=100 Ω, C_{b3b}=1 nF, R_{PD1}=1 kΩ, C_{PD1}=100 nF. Note that the negative supply -V_{PD} must be set according to the photodiode data sheet.

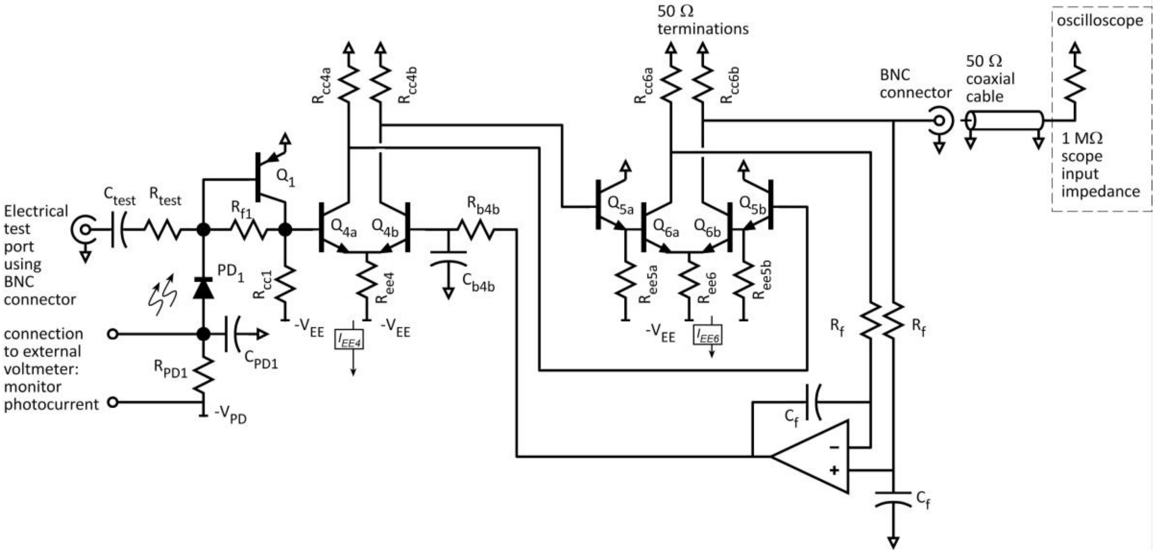

Figure 12: Example using a PNP TIA. The DC level interface between this and the NPN differential stage requires fewer transistors. R_{F1}=1 kΩ, R_{test}=100 kΩ, C_{test}=10 nF, R_{b4b}=100 Ω, C_{b4b}=1 nF, R_{PD1}=1 kΩ, C_{PD1}=100 nF. Note that the negative supply -V_{PD} must be set according to the photodiode data sheet.

Figure 11 and Figure 12 show example designs. In the design of Figure 11, an NPN TIA stage (Q1) is followed by an emitter-follower level shifter (Q2 and diode-connected transistor D1), followed by a pair of differential gain stages (Q4ab with emitter followers Q3ab, Q5ab with emitter followers Q5ab). You may or may not need a third differential gain stage to meet the gain specification while obtaining the bandwidth you seek.

The transimpedance load resistance Rf1 must be at least 1 kOhm. Larger values than this will improve noise (sensitivity) but degrade bandwidth (maximum bit rate).

By setting Rcc6a=Rcc6b=50 Ohms, the overall amplifier output impedance is 50 Ohms, allowing it to interface to a 50 Ohm coaxial cable without signal distortion. The receiving end of the cable, the oscilloscope, is loaded with the very high 1 MOhm scope input impedance.

As you can easily calculate, the maximum peak-peak output voltage of Q6ab is $I_{EE6}R_{cc6b} = I_{EE6}(50\Omega)$; this will set a minimum bias current for the stage. You must also consider the effect of saturation on maximum peak-peak output voltage.

The $R_{b3b}C_{b3b}$ network provides a local high-frequency bypass to the base of Q3. The capacitor must be large enough to provide a good AC ground to the base of the transistor but the product $R_{b3b}C_{b3b}$ Must be small enough to not add excess phase to the low frequency DC restoration feedback loop. I recommend a resistance of 100 ohms and a capacitance of 1 nF.

Figure 12 shows a similar circuit using a PNP transimpedance amplifier. The DC level interface between this and the NPN differential stage requires fewer transistors. The design discussion is similar to that the earlier design. Once again you may need three differential stages to get adequate gain with the target bandwidth.

Regarding the transimpedance amplifiers, these can be analyzed using negative feedback theory, by using MOTC, or by nodal analysis. When using MOTC, be sure to note that the feedback connections strongly change the impedance presented to various capacitors.

The specific assignment

first check off date

Construct and demonstrate a functioning pseudo random data generator. Determine the maximum clock frequency at which it works properly. Verify that the pattern is stable and repetitive.

second check off date

Your objective is to produce the fastest possible transmitter.

Demonstrate a pulse driver (transmitter) circuit connected to the pseudo random data generator. Measurements to be made include

-risetime and full-time of the optical waveform

-percent overshoot or undershoot in the optical waveform, if ringing is present. This must be less than 15% if the receiver is to function.

- percent droop or sag in the optical waveform, if present. This must be less than 10% if the receiver is to function. This would arise if the zero is added to the transmitter, but is incorrectly adjusted relative to the pole associated with the LED capacitance.

- the zero-state LED current is to be less than 1 mA, while the on-state LED current is to be greater than 10 mA.

-maximum data rate for a discernable data pattern on the oscilloscope.

third check off date

At this point, the receiver has also been completed. Your objective is to produce the fastest and most sensitive possible receiver. The receiver must have gain sufficient to produce a 250 mVpp output with a measured 2 uA DC photocurrent input. The photodiode load resistance must be at least 1000 Ohms. A transimpedance front end is required.

Note that sensitivities below ~ 1 uA photocurrent will likely be unattainable at data rates of ~10 MHz. At this level, electrical noise becomes a limit.

The low-frequency cutoff must be below 1 kHz.

Measurements to be made include

Test # 1: **Small-signal sinusoidal gain-frequency characteristics:** With no optical input, measure the gain-frequency characteristics of the receiver using the test electrical input. The signal generators in the lab have 50 Ohm output impedance and the front-panel display gives the output voltage that would be delivered to a 50 Ohm external load;

the Thevenin open-circuit output voltage of the generator is therfore 2:1 times larger than the front-panel display: measure the signal generator output on an oscilloscope to verify this. With R_{test} =100 kOhm, and with a signal generator set at a signal voltage V_x, the AC current forced into the transimpedance amplifier input would be $2V_x / (50\Omega + R_{test}) \cong 2V_x / R_{test}$.

Set the signal generator to a sine wave, with V_x = 10 mV peak-peak, giving a 0.2 μA peak-peak input current. Make sure that the amplifier output is not clipping; if necessary, reduce the peak-peak input voltage V_x.

Set the signal generator frequency to 500 kHz (mid-band). Measure the peak-peak output voltage. The resulting mid-band transimpedance gain is $Z_T(500\text{ kHz}) = V_{out,peak-peak}R_{test} / V_{x,peak-peak}$. **Record this measurement**.

Reduce the signal generator frequency while measuring the transimpedance gain. Determine the lower frequency at which the transimpedance gain is reduced 3 dB (0.707:1 in voltage) relative to that of mid-band. This is your lower -3 dB frequency. **Record this measurement**.

Increase the signal generator frequency while measuring the transimpedance gain. Determine the upper frequency at which the transimpedance gain is reduced 3 dB (0.707:1 in voltage) relative to that of mid-band. This is your upper -3 dB frequency. **Record this measurement**.

Test # 2: **Large-signal sinusoidal maximum voltage characteristics:** Continuing with an electrical input, as in test #1, determine the maximum undistorted linear peak-peak output voltage at 500 kHz (mid-band). **Record this measurement**, **recording both the numbers and an image of the waveform**. **Please include this image in your report.**

Test # 3: **Small-signal time-domain characteristics:** Continuing with an electrical input, as in test #1, **with a peak-peak voltage V_x small enough that the amplifier is not clipping** (as determined by test #2 above) , set the signal generator to a square wave. Measure the 10%-90% risetime of the output waveform. If there is overshoot, measure the percentage. **Record this measurement**, **recording both the numbers and an image of the waveform**. **Please include this image in your report.**

Then, reducing the square wave frequency and increasing the oscilloscope sweep time, measure the time at which the step response droops back to 50% of the initial step response. **Record this measurement**, **recording both the numbers and an image of the waveform**. **Please include this image in your report.**

Test # 4: **Functional test as an optical receiver; square wave test:** Disconnect the electrical input, and connect the receiver to the transmitter with an optical fiber. Drive the

LED or laser transmitter with a square-wave input, not the PRBS data generator. Partially remove the optical fiber from the photodiode, monitoring the photocurrent until is approximately 2 microamps (DC voltage across R_{PD1} = 2 mV). Measure the 10%-90% risetime of the output waveform. Hint: use signal averaging to reduce the noise. If there is overshoot, measure the percentage. **Record this measurement**, **recording both the numbers and an image of the waveform**. **Please include this image in your report.**

Test # 5: **Functional test as an optical receiver; random data test:** Disconnect the electrical input, and connect the receiver to the transmitter with an optical fiber. Drive the LED or laser transmitter with the PRBS data generator. Partially remove the optical fiber from the photodiode, monitoring the photocurrent until is approximately 2 microamps (DC voltage across R_{PD1} = 2 mV). Measure the data waveform as a function of bit rate, and determine the maximum data rate with correct "1" an "0" levels of isolated bits always at on the correct side of the voltage level equidistant between the asymptotic 1 and 0 levels. . **Record this measurement**, **recording the maximum data rage and an image of the waveform**. **Please include this image in your report.**