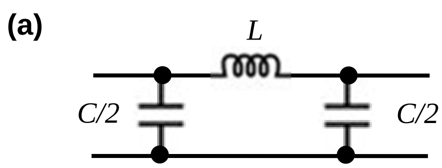
ECE 4880 RF Systems Fall 2016
Homework 3 Solution
Due 9/16 5pm in the Phillips Hall Dropbox

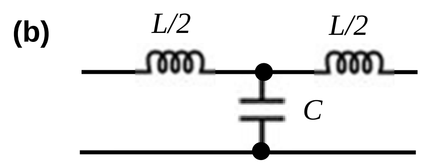
Reading before homework:

- Lecture note Chap. 2
- Lee's *The Design of CMOS Radio Frequency Integrated Circuits*, 2^{nd} *Ed.*, Chap. 3.

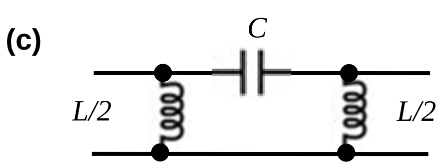
1. (**Filter by LC Banks**) Filters are used extensively in RF systems and the passive filters are often accomplished by LC resonators. For the following four filters, denote whether they are low-pass or high-pass. Note that the π and T network construction is often popular due to its symmetry (see Prob. 2). (**12 pts**)



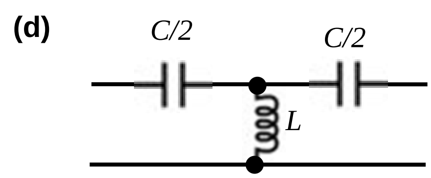
?-pass π section



?-pass T section

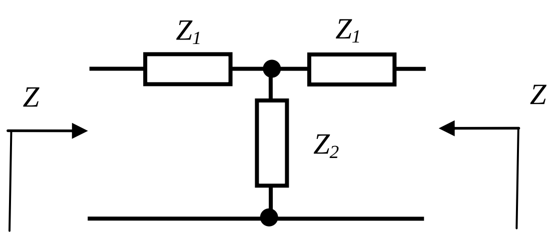


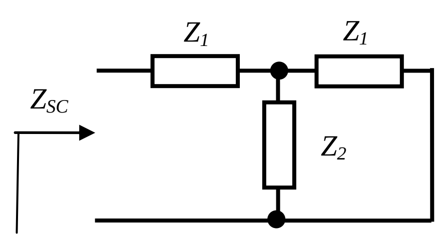
?-pass π section



?-pass T section

2. (**The image impedance method in filter design**) To find the impedance for the π and T networks above, the image impedance method offers a convenient view, which is often employed in the filter design for easier impedance characterization. Consider the T network below. Due to symmetry, we can conclude that both sides have the same *Z*.





(a) Derive $Z^2 = Z_1^2 + 2Z_1Z_2$ (**5 pts**). This will be the impedance when you have a large number of these modules in cascade.

(b) We define the short-circuit impedance Z_{SC} at the left end when the right end is short circuited (shown as an example in the right), and the open-circuited impedance Z_{OC} at the left end when the right end is open circuited. Derive $Z = \sqrt{Z_{OC}Z_{SC}}$. (**5 pts**) This relation offers an easy method for measuring the impedance of the T network.

(c) If $Z_1 = j\omega L/2$ and $Z_2 = 1/j\omega C$, what is the impedance *Z* of this T network in Prob. 1b as a function of frequency? (**5 pts**) Draw *Z* vs. ω in the Bode plots of |Z| and ∠Z. (**10 pts**)

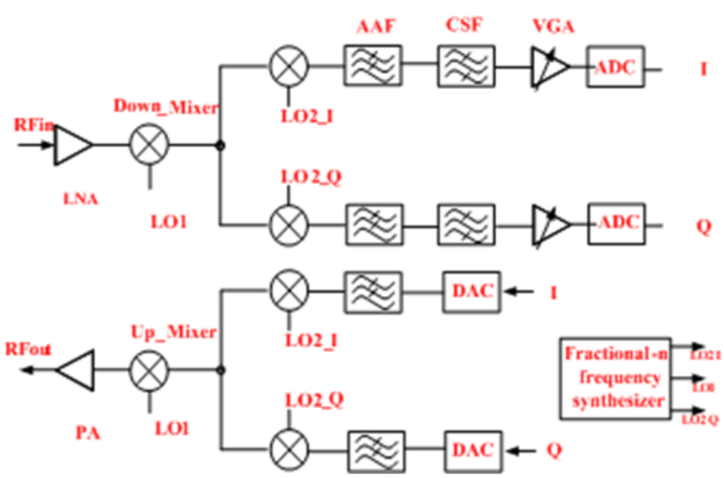
3. **(Practice of dB and dBm**) Translate to or back from dB, dBm or dBi for the following (**3 pts** each)
   (a) An RF amplifier with power gain of 100 and voltage gain of 10. Answer the amplifier gain in dB.
   (b) An antenna with 8 dBi in reference with an imaginary isotropic lossless antenna. Answer the ratio of peak power in this antenna and the imaginary isotropic antenna.
   (c) A differential amplifier with voltage gain of 40. Answer the amplifier gain in dB.
   (d) A filter with pass-band power loss of −3dB and stop-band power loss of at least −60dB. What are the percentage of transmitted power in the pass-band and stop-band?
   (e) A power amplifier with 36dBm maximum output power. Answer in Watt.
   (f) A power amplifier with 0dBm input and 30dB gain. What is the output power in dBm?

4. (**Superheterodyne RF transceiver block diagram**) We have not covered this in the lecture, so the problem is simple and self contained. Just as a warm-up for the lecture on "Idealized transceiver design". Assume the local oscillator 1 (LO1) implements the carrier frequency of 900MHz, and LO2 implements the intermediate frequency (IF) of 10.7MHz. This is called the superheterodynae scheme. The quadrature elements *I* and *Q* are for phase/magnitude handling/extraction and improved linearity (reasons will be clear in the long run). *I* and *Q* are sometime the same signal with 90^o phase shift. The 10-bit ADC and DAC have the sampling data at 200kHz. Assume that the ADC and DAC will take voltages roughly from 1mV to 1V without severe distortion/underflow/overflow (for example 1mV at ADC will give 0000000001_2 and 1V will roughly give 1111111111_2). Follow through the ideal signal chain in the following questions. The mixer is implementing the simplified function for frequency conversion:

$$v_{in} = A(t)\sin(\omega_{in} t); \qquad v_{LO} = C\sin(\omega_{LO} t;);$$

$$v_{out} = \frac{CA(t)}{2}\left(\cos((\omega_{LO} + \omega_{in})t) + \cos((\omega_{LO} - \omega_{in})t)\right),$$

where *A(t)* is a slow-varying function in time.
We will temporarily ignore the frequency synthesizer, and assume all desired LO frequencies are available.



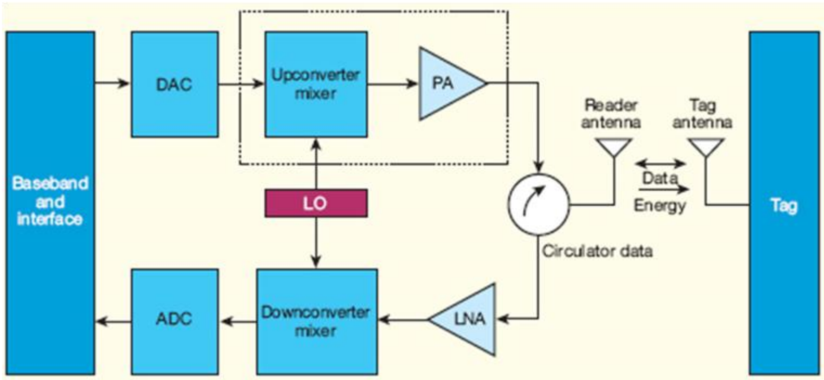
- LNA: low-noise amplifier
- I, Q: quadrature signals
- Down_mixer: down-conversion mixer
- LO: local oscillator
- AAF: anti-aliasing filter (low-pass)
- CSF: channel select filter (band-pass)
- VGA: variable gain amplifier
- ADC: analog-to-digital converter
- DAC: digital-to-analog converter
- Up_mixer: up-conversion mixer
- PA: power amplifier

   (a) What frequency should the low-pass filter to the right of the LO2 mixer be? Give a rough estimate. What are the operating frequency range of the LNA and PA? (**5 pts**)
   (b) Assume RF_{in} in the receiver is in the range of 1pW (–90dBm) to 0.1mW (–10dBm), as we do not know how close the other radio is, and the dynamic range here is 10^8 or 80dB, a common number. Further assume that the receiving antenna as well as the input impedance of LNA is 50Ω, what is the voltage level at RF_{in}? (**5 pts**)

(c) For the minimum signal at RF_{in}, how much gain is needed for the ADC to recognize the signal? (**5 pts**)

(d) The range of the minimum and maximum voltage of RF_{in} is too large for the 10-bit ADC. This is where the variable gain amplifier (at the low-frequency baseband, so not hard to implement). What is the minimal range of gain the VGA needs to provide? (**5 pts**)

5. (**Backscattering RF transceiver considerations**) A typical RFID reader transceiver block diagram is shown below. Notice that this is a "homodyne" amplitude-modulation transceiver, and much simpler than the superheterodyne quadrature modulation transceiver in the previous problem.



The operation is that the reader sends a modulated RF signal and listens to the echo from the RFID tag. The passive tag needs to collect power from the RF carrier, and run a small logic signal to put modulation on the echo. The RFID system is most often limited by the tag sensitivity, i.e., the tag needs to convert enough RF power from the RF carrier sent by the reader. Therefore, many other parts of the radio are adapted for that purpose. The transceiver in the tag is even more simplified, because if the carrier is powerful enough for run the logic circuits, the radio signal is very strong and easy to design.

(a) What is the different requirement in the local oscillator here in comparison with that of the quadrature superheterodyne transceiver in problem 4, in terms of number of LO generators and frequency accuracy? (**5 pts**)

(b) The transmitter and the receiver share one antenna through a component called "circulator". The circulator has low loss from PA to antenna as well as from antenna to LNA, but high "isolation" from PA to LNA directly. A duplex transceiver can use an RF switch to time share the antenna, but here as the tag can only be on with the transmitter on, time sharing is not possible and a circulator is necessary. Assume the circulator pass-path has –1dB loss, and –60dB loss for stop-path, when the PA outputs 36dBm power, what is the power of the self jamming signal at the LNA? (**5 pts**) If the receiver has a –70dBm sensitivity (i.e., the lowest echo to be heard clearly has power of –70dBm), what is the power ratio between the self jamming and the lowest echo? (**5 pts**) (very simple, just for your familiarity with dB calculation in a signal chain context)

(c) At the –70dBm receiver sensitivity (i.e., the lowest echo to be heard has power of –60dBm), what is the peak voltage for 50Ω impedance? (**5 pts**) As we do not use a variable-gain amplifier here, for a 12-bit ADC (analog-to-digital converter), what is the largest power (in mW and dBm) and peak voltage at the LNA input without causing overflow? What is the dynamic range of the receiver in dB? (**5 pts**)