OLLSCOIL NA hÉIREANN, CORCAIGH
THE NATIONAL UNIVERSITY OF IRELAND, CORK

COLÁISTE NA hOLLSCOILE, CORCAIGH
UNIVERSITY COLLEGE, CORK

AUTUMN EXAMINATIONS, 2007

B. E. (ELECTRICAL)
B.E. (MICROELECTRONICS)
M.ENG.SC. (MICROELECTRONICS)
H.DIP. (MICROELECTRONICS)

RF IC Design
EE4011

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Answer *five* questions.

All questions carry equal marks.
The use of a Casio fx570w or fx570ms calculator is permitted.
The use of mathematical/statistical tables is permitted.
Smith charts are appended to this paper. Detach and use as required. Write your examination number on any charts you use and return them with your examination script.

The following physical constants may be used as appropriate:
Boltzmann's Constant: $k = 1.38 \times 10^{-23}$ J/K
Elementary Charge: $q = 1.602 \times 10^{-19}$ C
Vacuum Permittivity: $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m

Time allowed: *3 hours*

1. (a) Show a small-signal model of a MOS transistor suitable for first-order analysis and from this derive an expression for the cut-off frequency. Assume the transistor is biased in saturation and that the current can be approximated by:

$$I_{DS} = \frac{1}{2}\frac{W}{L}\mu C_{OX}(V_{GS} - V_{TH})^2(1 + \lambda V_{DS})$$

where the symbols have their usual meaning. Also assume that the only capacitance to be considered is the gate-source capacitance.

[*10 marks*]

(b) An NMOS transistor is biased in saturation and configured as a common-source two-port amplifier with the input applied to the gate (port 1) and the output taken from the drain (port 2) with the following bias conditions and device parameters:

W=10μm, L=0.25μm, T_{ox}=4nm, μ=400cm^2/Vs, V_{GS}=2.0V, V_{DS}=3V, V_{TH}=0.7V, λ=0.1 V^{-1}, ε_r = 3.9 (relative permittivity of gate oxide).

Determine:

(i) The cut-off frequency

[2 *marks*]

(ii) The 4 two-port z-parameters at a frequency of 1.5GHz.

[8 *marks*]

Note: Express the calculated z-parameters in polar form with the angles in degrees.

2. (a) Show a small-signal model of a bipolar junction transistor (BJT) suitable for first-order analysis and from this derive an expression for the cut-off frequency of the transistor in a common-emitter configuration. Assume the transistor is biased in the forward active region with currents given by

$$I_C = I_S e^{\frac{qV_{BE}}{kT}}\left(1+\frac{V_{CE}}{V_A}\right) \quad , \quad I_B = \frac{I_C}{\beta}$$

where the symbols have their usual meaning. Only consider capacitances associated with the base-emitter circuit.

[*10 marks*]

(b) A BJT is configured as a common-emitter two-port amplifier with the input applied to the base (port 1) and the output taken from the collector (port 2).
The cut-off frequency has been measured at a temperature of 300K for two values of collector current as follows:

For I_C = 1mA, f_T = 1.5 GHz
For I_C = 10mA, f_T = 2 GHz

For this device, estimate (i) the forward base transit time and (ii) the base-emitter junction capacitance (the bias dependence of the base-emitter junction capacitance may be ignored for this calculation).

[*8 marks*]

(c) Based on the equivalent circuit and the element values determined in 2(a), determine the cut-off frequency of the transistor.

[2 *marks*]

3. (a) If the input of a balanced (differential) RF amplifier consists of two cosinusioidal waveforms with amplitudes A_1 and A_2 (V) and frequencies ω_1 and ω_2 (rad/s) respectively, the output waveform is given by:

$$
\begin{aligned}
y(t) = &\left[\alpha_1 A_1 + \frac{3}{4}\alpha_3 A_1^3 + \frac{3}{2}\alpha_3 A_1 A_2^2\right]\cos(\varpi_1 t) \\
&+ \left[\alpha_1 A_2 + \frac{3}{4}\alpha_3 A_2^3 + \frac{3}{2}\alpha_3 A_1^2 A_2\right]\cos(\varpi_2 t) \\
&+ \frac{1}{4}\alpha_3 A_1^3 \cos 3\varpi_1 t + \frac{1}{4}\alpha_3 A_2^3 \cos 3\varpi_2 t \\
&+ \frac{3}{4}\alpha_3 A_1^2 A_2 \cos(2\varpi_1 + \varpi_2)t + \frac{3}{4}\alpha_3 A_1^2 A_2 \cos(2\varpi_1 - \varpi_2)t \\
&+ \frac{3}{4}\alpha_3 A_1 A_2^2 \cos(2\varpi_2 + \varpi_1)t + \frac{3}{4}\alpha_3 A_1 A_2^2 \cos(2\varpi_2 - \varpi_1)t
\end{aligned}
$$

Using the formula for y(t) as a starting point and assuming that α_1 and α_3 have opposite signs, define and derive expressions for the following:

(i) The 1dB gain compression point (P1dB)

[5 *marks*]

(ii) The input-referred 3rd-order intermodulation intercept point (IIP3)

[5 *marks*]

(b) An amplifier such as the one described in part (a) has a single-frequency input with amplitude $10mV_{rms}$. The output at the fundamental is measured as $500mV_{rms}$ and the 3rd-harmonic output is measured as $8nV_{rms}$. Determine the 1dB compression-point of the amplifier.

[*5 marks*]

(c) Based on the expression for y(t) outlined in part (a) discuss two other undesired effects resulting from amplifier non-linearity in addition to P1dB and IIP3.

[*5 marks*]

4. (a) Describe the principles of operation of a high-frequency balanced amplifier.

[*7 marks*]

(b) A microwave bipolar junction transistor has the following characteristics (at 5 GHz with 50 Ω reference);

$$S_{11} = 0.5 \angle -135°$$
$$S_{12} = 0.05 \angle 30°$$
$$S_{21} = 2.65 \angle 195°$$
$$S_{22} = 0.5 \angle -45°$$

Check the stability of the device and design an input matching network for maximum power gain.

[*13 marks*]

5. (a) What do you understand by the "unilateral figure of merit" of a high-frequency amplifier?

[*8 marks*]

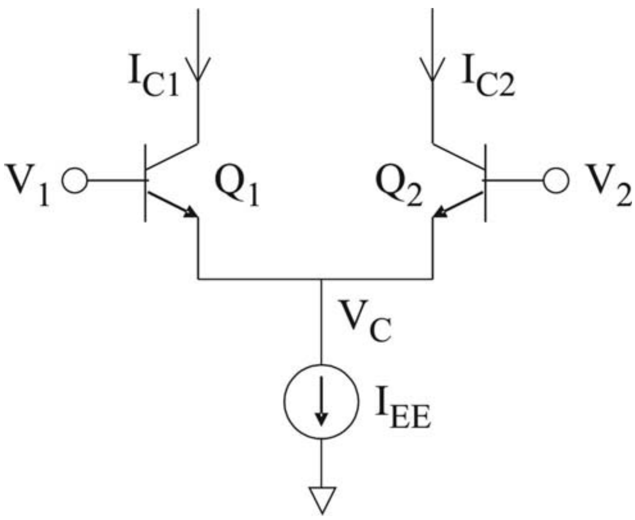
(b) Identify and discuss the sources of low-frequency errors in direct conversion receivers.

[*6 marks*]

(c) Discuss, using illustrative diagrams, the importance of the *image frequency* in a standard super-heterodyne transceiver architecture.

[*6 marks*]

6. (a) The circuit below shows a bipolar common-emitter pair formed using identical transistors Q_1 and Q_2 and a current source I_{EE}.



Determine an expression for the difference between the collector currents ($\Delta_{IC} = I_{C1} - I_{C2}$) as a function of the differential input voltage ($\Delta V = V_1 - V_2$).

[*12 marks*]

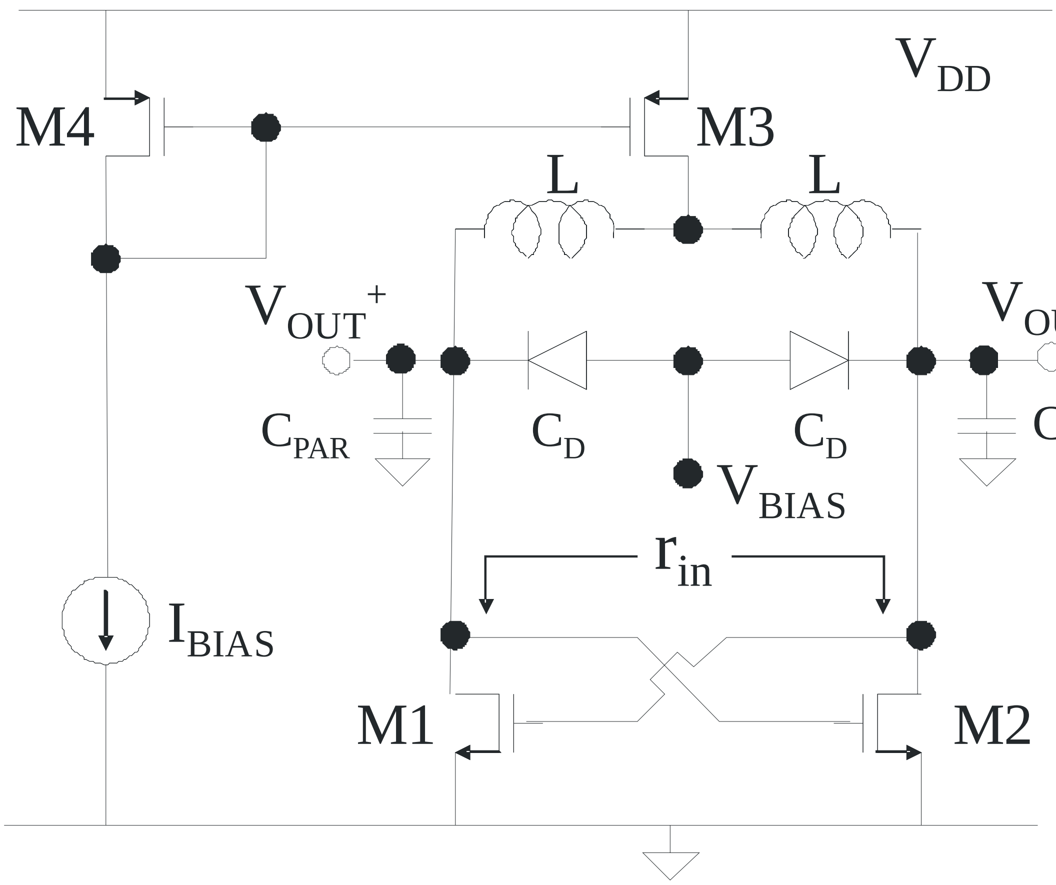
(b) Describe two techniques which can be used to increase the dynamic range of emitter-coupled pairs such as illustrated in (a).

[*4 marks*]

(c) Illustrate, using a circuit diagram, how emitter coupled pairs such as shown in (a) can be combined to form a Gilbert-cell double-balanced mixer for RF applications.

[*4 marks*]

7. (a) The schematic below shows a typical MOSFET LC Voltage Controlled Oscillator (VCO)



By using a suitable small-signal analysis, derive the equivalent input resistance (r_{in}) of the cross-coupled MOSFET pair above and specify the necessary condition for oscillation.

[*10 marks*]

(b) The VCO in (a) uses inductors (L) with a value of 3nH and has parasitic capacitances (C_{PAR}) of 1pF (including the MOSFET drain capacitances) at each of the output nodes. The diodes have parameters $M_J = 0.5$ and $V_J = 0.8$V. Determine the zero-biased diode capacitance needed to give a minimum oscillation frequency of 1.8GHz and using this value of zero-bias capacitance, determine the reverse bias voltage (V_{BIAS}) needed to increase the frequency to 2GHz.

[*10 marks*]

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