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

COLÁISTE NA hOLLSCOILE, CORCAIGH
UNIVERSITY COLLEGE, CORK

SUMMER EXAMINATIONS, 2008

B. E. (ELECTRICAL)
B.E. (MICROELECTRONICS)
M.ENG.SC. (MICROELECTRONICS)
Ph.D. (MICROELECTRONICS)
VSEU (VISITING EUROPEAN)

RF IC Design
EE4011

Professor C. Delabie
Professor P. J. Murphy
Dr. K. G. McCarthy

Answer *five* questions.

All questions carry equal marks.
The use of departmental approved non-programmable calculators 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 if necessary:
Boltzmann's Constant: $k = 1.381 \times 10^{-23}$ 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 derive an expression for the cut-off frequency of the transistor. Assume that 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*]

Question 1 is continued on the next page

1. (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:

$W = 20\mu m$, $L = 0.25\mu m$, $T_{ox} = 4nm$, $\mu = 350 cm^2/Vs$, $V_{GS} = 2.5V$, $V_{DS} = 2V$, $V_{TH} = 0.6V$, $\lambda = 0.15\ V^{-1}$, $\varepsilon_r = 3.9$ (dielectric constant of oxide).

Determine:

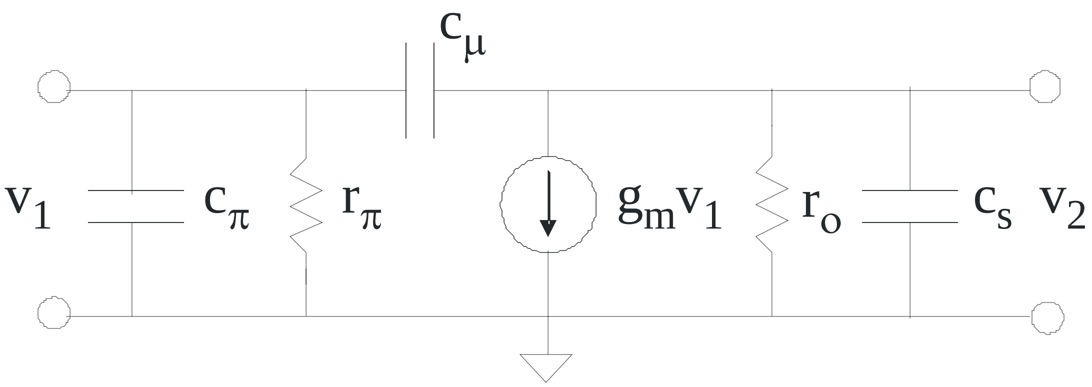
(i) The cut-off frequency

[2 *marks*]

(ii) The 4 two-port y-parameters at a frequency of 1GHz.

[8 *marks*]

2. (a) A bipolar transistor with the following equivalent circuit has been measured at a frequency of 2 GHz using a y-parameter set-up with port 1 corresponding to the input, v_1, and port 2 corresponding to the output, v_2.



The measured y-parameters are as follows:

$y_{11} = 0.0754\angle 88.1°$
$y_{12} = 0.0126\angle -90°$
$y_{21} = 0.1008\angle -7.16°$
$y_{22} = 0.0377\angle 89.2°$

From these y-parameters determine the values of the 6 elements of the equivalent circuit.

[16 *marks*]

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

[4 *marks*]

3. (a) 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 as follows:

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

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*]

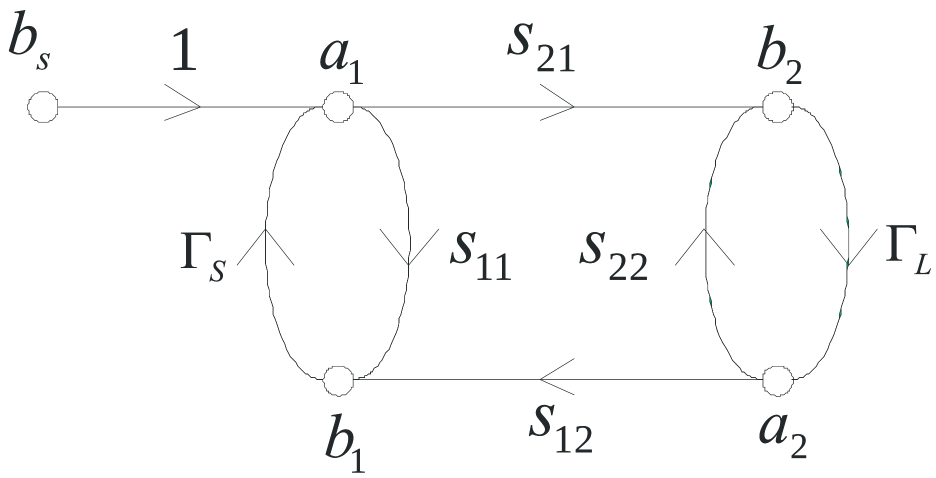
(b) An amplifier such as the one described in (a) has a single-frequency sinusoidal input with amplitude $2mV_{rms}$. The output at the fundamental is measured as $300mV_{rms}$ and the 3rd-harmonic output is measured as $2nV_{rms}$. Determine the 1dB compression-point of the amplifier.

[*5 marks*]

(c) Show a graphical means by which the input-referred third-order intercept point (P_{IIP3}) of an amplifier can be determined by measuring the fundamental output power and the 3rd-order intermodulation output power of an amplifier for a single input power level. Clearly identify all important parts of your diagram.

[5 *marks*]

4. For a single-transistor RF amplifier the signal flow from source to load can be represented by the following diagram where the symbols have their usual meanings.



(a) For an RF amplifier circuit give definitions for (i) the operating power gain, (ii) the transducer power gain and (iii) the available power gain.

[*3 marks*]

(b) Using the signal flow diagram above as a starting point, derive an expression for the operating power gain of a single-transistor amplifier.

[*14 marks*]

(c) A high-frequency transistor has the following characteristics (at 4 GHz with 50Ω reference):

$$s_{11} = 0.863 \angle -79.1°$$
$$s_{12} = 0.072 \angle 36.5°$$
$$s_{21} = 3.434 \angle 106.2°$$
$$s_{22} = 0.627 \angle -58.3°$$

Determine the operating power gain if this transistor is used as a single-transistor amplifier at 4 GHz assuming that the load reflection coefficient is set to zero ($\Gamma_L = 0$).

[*3 marks*]

5. (a) Outline the design procedure for an RF Low Noise Amplifier (LNA).

[*5 marks*]

(b) A GaAs MESFET is used in an LNA. It has the following s-parameters at 3 GHz (with 50Ω reference):

$$s_{11} = 0.38\angle -169° \quad s_{12} = 0 \quad s_{21} = 1.33\angle -39° \quad s_{22} = 0.95\angle -66°$$

Determine the maximum values for the source and load gain terms and the maximum unilateral transducer gain of the LNA at 3 GHz.

[*3 marks*]

Question 5 is continued on the next page

5. (c) Using Smith-Chart procedures, determine component values for the 2-element input and output matching networks for the LNA in (b) if the desired source gain is 0.3 dB and the desired load gain is 4 dB, where the source and load impedances are both 50Ω.

[*12 marks*]

Note:
The following equations specify the source gain circle where the symbols have their usual meanings:

$$|C_S| = \frac{g_s|s_{11}|}{1-|s_{11}|^2(1-g_s)} \qquad R_S = \frac{\sqrt{1-g_s}\left(1-|s_{11}|^2\right)}{1-|s_{11}|^2(1-g_s)}$$

The load gain circle is defined by a similar set of equations with appropriate changes.

6. (a) Illustrate a simple RF mixer based on a switch. From the illustration derive an expression for the frequency components in the output waveform and the voltage conversion gain of the mixer. Assume that the RF input has a co-sinusoidal form, $V_{RF}\cos(\omega_{RF}\, t)$.

[*10 marks*]

Note that a square wave of frequency ω rad/s which toggles between 0 and 1V can be represented by the Fourier expansion:

$$s(t) = \frac{1}{2} + \frac{2}{\pi}\left[\sin(\varpi t) + \frac{1}{3}\sin(3\varpi t) + \frac{1}{5}\sin(5\varpi t) + \cdots\right]$$

(b) Draw a circuit diagram of a Gilbert multiplier based on bipolar transistors, clearly showing the connections of the RF and LO signals and the interconnections between the transistors.

[*4 marks*]

(c) Briefly describe the 3 possible operating modes of the Gilbert cell shown in (b).

[*6 marks*]

7. (a) Illustrate a Type 1 Phase Locked Loop (PLL) using an integer feedback divider.

[*4 marks*]

(b) Determine the closed-loop transfer function of the PLL in (a) making sure that the denominator follows the form of a standard second-order system where the symbols have their usual meaning:

$$s^2 + 2\varsigma\omega_n s + \omega_n^2$$

[8 *marks*]

(c) A Type 1 PLL using an integer feedback divider is to be used as a frequency synthesizer to generate frequencies from 935 MHz to 960 MHz in steps of 200kHz.

(i) Determine the appropriate input reference frequency.

[2 *marks*]

(ii) Determine the range of divider values to give the desired frequency range.

[2 *marks*]

(iii) Determine the cut-off frequency of the low pass filter using an appropriate rule of thumb.

[2 *marks*]

(iv) Determine the PLL gain constant ($K_{PD}K_{VCO}$) to give a damping factor of 0.707 i.e. a critically damped configuration.

[2 *marks*]