Laboratory #7: Introduction to RF Amplifier Design

I.   OBJECTIVES

Design an RF amplifier with microstripline stub impedance matching techniques. Simulate the
results using Agilent ADS

II.   INTRODUCTION

Impedance matching can readily be performed between 50 Ω generators or loads and arbitrary
complex impedances. Impedance matching to the input or output (base and collector) of an RF
transistor is no different. Given certain bias conditions, the S-parameters for the transistor are
specified in the data sheets. Therefore, the standard impedance matching techniques using
conjugate matching for maximum power transfer can be used.

Amplifier Design - Bias Networks
The necessary groundwork for designing a microwave frequency amplifier has all
been set; the remainder of this lab is a start towards designing an amp. The first part of
designing an amplifier is to find a circuit that will properly bias the microwave transistor at
the desired operating point but that will not interfere with the microwave operation of the
circuit.

1.) In designing a bias network, it is important to choose a design that will minimize the
"loading" of the RF signal, while still providing the correct dc bias conditions to the
transistor. For this design, it is necessary to supply a dc base current and collector voltage
bias, without loading the microwave signal present on the base and collector transmission
lines. Since we'll be supplying the bias in shunt (in parallel with the RF signal), this
means that the bias must be supplied through a network that presents a low resistance at
dc, but a high impedance at the operational frequency of the amplifier (700 MHz). A
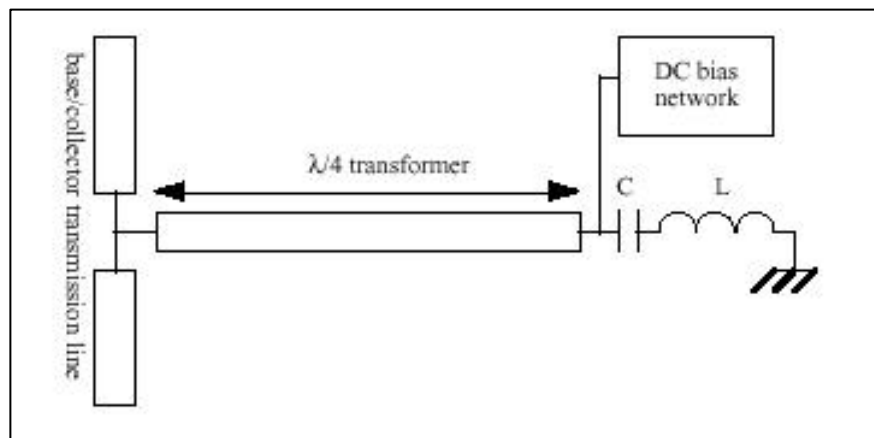straightforward way to achieve this is the circuit below:

Figure 1. Schematic illustrating bias stub concept.

The capacitor and inductor are realized using a series-resonant chip capacitor whose resonant frequency coincides with the amplifier's design frequency (700 MHz). At series resonance, the impedance of the inductor/capacitor pair is zero. You should verify that this is true for yourself. Thus, at the center frequency of the amplifier, the λ /4 section of transmission line acts as a short-terminated stub. Transforming short through a quarter-wavelength results in an infinite input impedance at the center frequency; thus at 700 MHz the bias stub will not load the main transmission line. At dc, however, the chip capacitor has infinite impedance, and so the DC network circuit is not loaded by the stub or capacitor. Thus we have found one possible bias network that is suitable for the amplifier design. The "linecalc" feature of ADS is convenient for performing these types of designs.

a) Create a schematic design that will become your amplifier circuit design. Insert an MSUB element with the substrate parameters you found from lab 6. Insert a microstrip transmission line. Rotate the line so that it is oriented vertically on the schematic; this will become one of the bias stubs for your circuit. Add a series inductor (1.5 nH) and a capacitor to the "top" end of the bias stub. For the series inductance of 1.5 nH, what capacitance is needed for resonance at 700 MHz? Set the capacitor to this value.

b) The design of a bias stub consists of determining the appropriate width and length for the microstrip transmission line in order to transform the resonant *LC* circuit to an open circuit. Linecalc contains models for microstrip transmission lines that are accurate over a wide range of frequencies and dimensions, and it ideal for this type of calculation. To start linecalc, select the bias stub transmission line (single-click), and choose "Tools/LineCalc/Send Selected Component to LineCalc" from the menu. This will automatically transfer the substrate parameters and appropriate transmission line model to linecalc. In the linecalc window, set the frequency to 700 MHz. For the width of the transformer line, use W=100 mil; selection of a narrow width makes for a transmission line with large characteristic impedance, and thus a higher input impedance even if the line is mistuned somewhat. After setting the width, press the "analyze" button. This will calculate the electrical properties (loss, characteristic impedance, electrical length) of the line. The electrical length will probably not be what is desired. Recalling that electrical length = $\beta l = 2\pi l / \lambda$, find the desired length in degrees. Set the electrical length, and have linecalc compute the physical length by pressing the "synthesize" button. Linecalc has now found a λ /4 transformer at 700 MHz with a width of 100 mils.

c) To incorporate this calculation into the schematic page, select "Tools/LineCalc/Update Selected Component" from the menu. The dimensions of the line will automatically be updated to those found in linecalc.

d) Since two bias stubs are required (one to supply the base current, one to supply the collector voltage), copy this stub (and the inductance and capacitance) to another position in the schematic.

2.) Now that the bias stubs have been designed, the circuit to supply the bias current and voltage must be designed. There are many circuits that can be used, ranging from resistive bias networks to current-source biasing schemes and even more complex

designs with temperature compensation. Select an approach, and using DC data acquired earlier in the lab design a circuit to bias the transistor. A number of references are available to help you in selecting a topology. Notice that at GHz the resonant LC circuit will act like a short-circuit, and so the details of your circuit selection will not strongly affect the operation of the amplifier at microwave frequencies.

Amplifier Bias Circuit Layout

With the bias stubs designed, we're ready to begin laying out the design of the amplifier circuit. Figure 2 below shows a view of the bias portion of the completed amplifier. Use lincalc to find the dimensions (width only) for the base and collector input lines, assuming a 50 . characteristic impedance at 700 MHz. At this point the length of these lines is arbitrary and will be set later in the design process. Insert transistor equivalent subcircuit, connect it to the input and output lines, and attach the bias stubs you've designed to the line at least 5 mm away from the transistor. Figure 3 shows an example circuit. As shown in Figure 3, you can use MTEE element to connect the bias stubs to the input and output line for accurate simulation of the transition there.
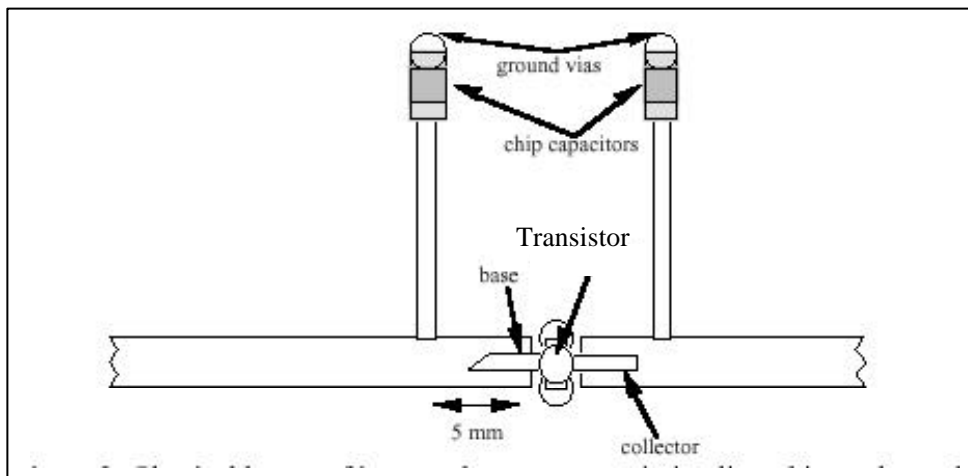

Figure 2. Physical layout of input and output transmission lines, bias stubs, and transistor.

2.) Simulate this circuit to make sure everything is working. The s-parameters should show some gain in s $_{21}$, and a clear resonance in S$_{11}$ and S$_{22}$ around 700MHz due to the bias stubs.
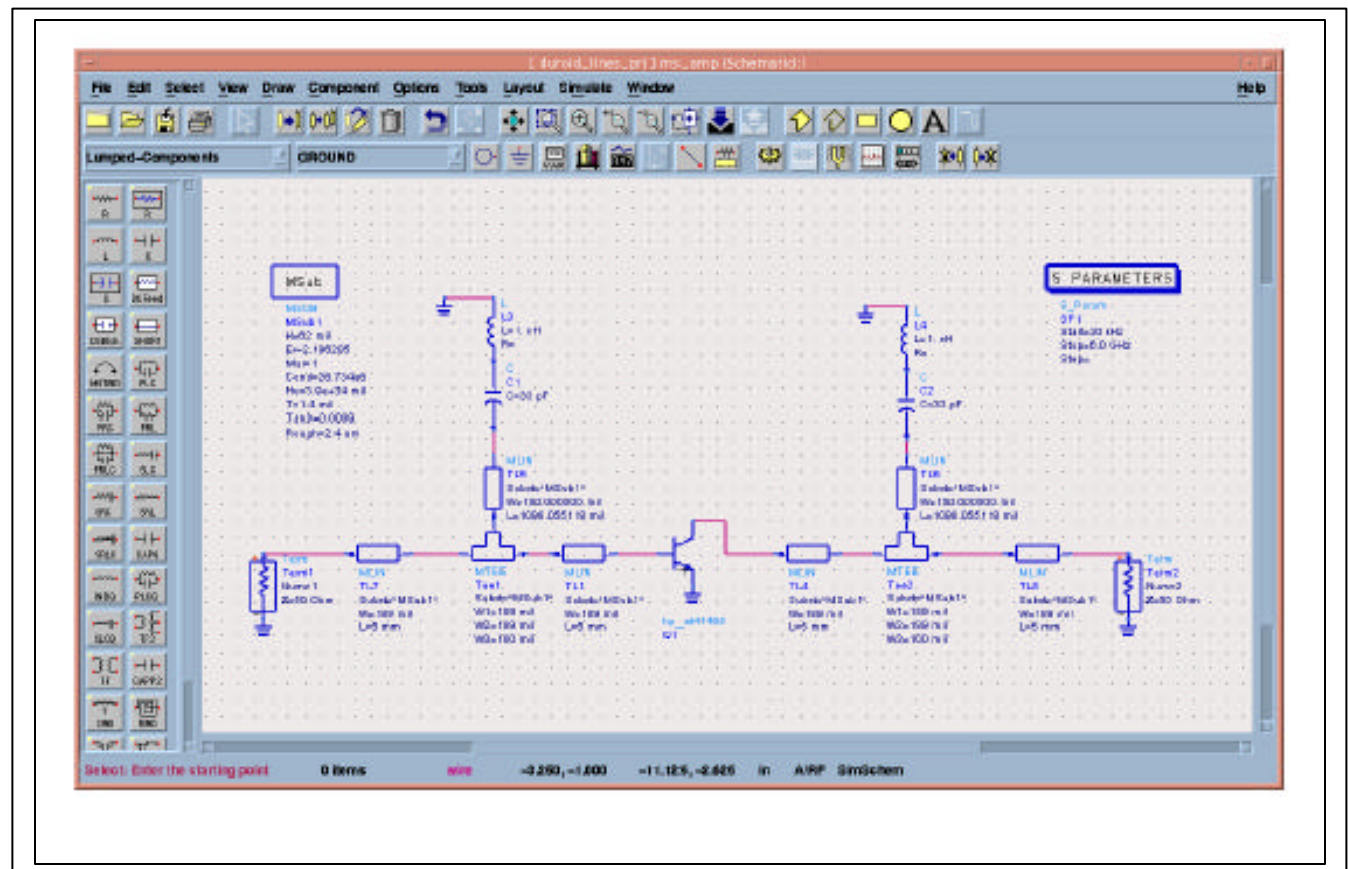
Figure 3. Sample schematic showing attachment of bias stubs.

Matching Network Design

Using the simulation results from above, design input and output matching networks to achieve a simultaneous conjugate match at both the input and output at 700 MHz. You may use single-stub, double-stub, quarter-wave transformer, or any combination of matching networks you choose. Use open-terminated stubs for your design; making a low-inductance, repeatable short-terminated stub is more difficult in practice. In working through your design, be alert for a few things:

    a.) Work through the design of the chosen topology by hand first, before going to the computer, to make sure sure there are no surprises. You may also wish to sanity-check your hand calculations using a Smith chart.

    b.) You may find it convenient to use equations on the data display page to calculate conjugate matching conditions, shunt susceptances, stub characteristic impedances, etc. One caveat: there is no built-in function in the equations for finding the complex conjugate of a number–use the expression cmplx(real(A),-imag(A)).

    c.) The characteristic impedances of the matching stubs should be chosen so that the lengths of these stubs are near $\lambda/8$ or $3\lambda/8$ (using open-terminated matching stubs). This length restriction is chosen to minimize the sensitivity of the match to the exact length of the stubs.

d.) Use linecalc to find the width of stubs on your substrate needed to get the desired characteristic impedance for each stub.

e.) You may use either balanced or unbalanced stubs at your discretion; the use of balanced stubs is often helpful if the width of an unbalanced stub is too wide.

f.) Since the matching stubs will be perpendicular to the main input and output lines, be sure that in your design the stubs do not overlap (or aren't too close to) the bias stubs or the transistor. You may need to adjust the length of line between the start of your matching network and the bias stub in order to have enough room; keep in mind that if you do this you must recalculate the simultaneous conjugate match conditions.

Matching Network Simulation and Optimization

1.) Enter the matching network designs that you found before lab into the amplifier schematic. Note that if you use MTEE elements to connect the lines and stubs together, you should adjust the length of the stubs downward by W/2 for the main line. This is necessary because the transmission line theory does not account for the finite width of transmission lines; it assumes that all lines are 1-dimensional. Add a length of 50 Ω line before any matching network on the input and after any matching on the output to allow for the input and output transmission lines. A good length is usually about half an inch.

2.) We'll also want to install DC blocking capacitors on the input and output lines to prevent the DC bias of the transistor from being loaded by the source and load, while still permitting the microwave signal to pass unimpeded. A series-resonant capacitor is nearly ideal for this purpose.

The design of an RF amplifier is not complete after impedance matching. Two other very important design issues must be resolved:

1. Is the amplifier stable – i.e. is it prone to oscillation?
2. What is the Transducer Power Gain G_T, Unilateral Power Gain G_{TU}, and Operating Power Gain G?

Another very important specification of a completed RF Amplifier is its Noise Figure *NF*. This figure quantifies the noise performance of the amplifier and can be used in noise analysis of systems.

These important RF Amplifier design issues are addressed in a handout that can be found on the course homepage.

III.   PROCEDURE

A.   *Bias the RF Transistor*
   - Bias the MRF581 RF Transistor to IC = 50 mA with VCE = 10V. The Operational Frequency is 700 MHz.

B.   *Design the Impedance Matching Stub Network*

C.   *Model the Circuit Suing ADS*
- Model the circuit using ADS and determine $\left|S_{11}\right|$, $\left|S_{22}\right|$, and $\left|S_{21}\right|$ on grid plots. Also plot $\left|S_{11}\right|$ and $\left|S_{22}\right|$ on Smith charts.
- Sweep the frequency of operation across the frequency bands of interest (500MHz - 1000 MHz).
- Remember to define the circuit as a two-port and terminate with the specified load and a perfect match at the input.

D.   *Analytically Determine the Gain and the Stability of the Amp*

E.   *Simulate the Amplifier Using ADS to Determine the Gain and the Stability*

F. *Comment on your results.*