Teaching Microwave Amplifier Design at the Undergraduate Level

Kimberley W. Eccleston, *Member, IEEE*

***Abstract*—Many textbooks on the subject of microwave amplifier design contain redundant material that may overload and confuse a student confronting microwave amplifiers for the first time. Some topics such as unilateral gain and unilateral design are often not necessary in this day of personal computing where exact gain and gain circle calculations can easily be used. Stability circles can be used to both identify allowable values of source and load reflection coefficients for the transistor and ascertain whether or not the transistor is unconditionally stable. By eliminating redundant topics and emphasizing the dual role of stability circles, instructors are able to effectively teach undergraduate students in a relatively short time design methods for narrow-band low-noise amplifiers, both single-stage and multistage, which employ either conditionally or unconditionally stable transistors.**

***Index Terms*—Amplifier stability, low-noise amplifiers, microwave amplifiers, multistage amplifiers.**

I. Introduction

THE amplifier is probably the most prolific of all electronic circuit building blocks in a microwave/radio-frequency (RF) system. Therefore, the instructor of a microwave/RF engineering course justifiably devotes a substantial amount of time to teaching the design of microwave amplifiers. At the very minimum, at the undergraduate level, such a course should equip students with the necessary knowledge and skills to design narrow-band low-noise amplifiers, both single-stage and multistage, using either conditionally stable or unconditionally stable transistors and microstripline technology. Arguably, the student should learn how to design wide-band and power amplifiers. However, at an undergraduate level, these concepts are either unnecessary or beyond the scope of a course that is expected to cover other topics, such as oscillators and mixers. Further, wide-band amplifiers find application primarily in specialized systems, such as electronic warfare systems, whereas narrow-band amplifiers find application in a wide variety of personal wireless communication systems. A course attempting to cover power amplifier design needs to cover large-signal modeling of microwave power transistors and harmonic balance analysis of nonlinear microwave circuits; both would require considerable expenditure of class time to cover adequately.

When teaching a course, the instructor must select a textbook that students can reference for more detail and further examples. A number of well known and highly regarded textbooks are available in the area of microwave engineering [1]–[4]. These books have a broad coverage and include the traditional topics of microwave engineering, such as electromagnetic waves, transmission lines, microwave circuit theory, resonators, and couplers, with some treatment of microwave electronic circuits such as amplifiers, mixers, and oscillators. In providing a broad coverage, compromises are necessarily made that are at the expense of adequate treatment of solid-state microwave amplifiers. Typically, the chapter on amplifiers occupies only a small fraction of the textbook. In some cases, the treatment is focused on simultaneous conjugate matching and the unilateral case, in which insufficient attention is paid to the use of conditionally stable transistors. Some texts omit low-noise amplifier design. A comprehensive text on microwave amplifier design [5], [6] is therefore highly recommended.

Almost all microwave amplifier textbooks consider design based on the unilateral approximation. Although unilateral approximations allow one to perform a design with a minimum of complex arithmetic, exact results for gain and gain circles, without the unilateral assumption, can easily be obtained from personal computers with access to mathematical software packages.

The well-known K stability factor, along with other conditions [5], [6], can be used to determine whether or not the transistor is unconditionally stable. Stability circles, however, are normally used to identify allowable values of source and load reflection coefficients for the transistor when it is conditionally stable. However, they can also be used to determine whether or not the transistor is unconditionally stable.

This paper describes the methods that can be used to teach undergraduate students—using only 9 h of lectures and 2 h of tutorials—design of narrow-band low-noise amplifiers, both single-stage and multistage, using conditionally stable transistors, as well as unconditionally stable transistors. This approach has been used at the National University of Singapore (NUS) in the course EE4104 Microwave Circuits and Devices. The prerequisite knowledge for this course is transmission lines. To achieve such a result in a short duration of time, the author has omitted analysis and design based on the unilateral approximation and has emphasized the dual role of stability circles in design. This course has been taught since 1993, both in its current and predecessor form.

Section II gives an overview of EE4104 at NUS. Section III discusses in detail the theoretical treatment used to teach microwave amplifier design in EE4104. Section IV discusses other practical considerations and issues. Finally, Section V concludes with a summary.

Manuscript received June 22, 2002; revised February 21, 2003.

The author is with the Department of Electrical and Computer Engineering, National University of Singapore, Singapore 119260 (e-mail: elekwe@nus.edu.sg).

Digital Object Identifier 10.1109/TE.2003.822635

II. Overview of EE4104 at the NUS

Students enrolled in the four-year B.Eng. program in electrical engineering at NUS are exposed to mathematics, physics, and core electrical engineering courses during their first two years. In their third and fourth years, they have opportunities to choose specialized electrical engineering elective courses comprised of 26 h of lectures, 6 h of tutorials, and 6 h of laboratory. Throughout the program, the student completes a number of projects of which their final year project is a major effort requiring a commitment of about 15 h per week over an academic year.

EE4104 Microwave Circuits and Devices is one of the electives in the microwave/RF area and has the following major sections (with lecture hours in parentheses): amplifiers (9 h), oscillators (4 h), planar microwave components (4 h), p-i-n switches and applications (4 h), and mixers and detectors (5 h).

EE4104 is assessed by two laboratory experiments (10% of the final grade), two assignments (20% of the final grade), and a final closed-book written examination (70% of the final grade). One of the assignments involves the design and simulation of a single-stage low-noise amplifier with each student being assigned a unique center frequency. The simulation using microwave CAD software, such as Agilent ADS [7] and Ansoft Serenade SV [8], is used not only to verify the design, but also to demonstrate the frequency response of the design. The student has an opportunity to design microstriplines and bias circuits and observe the effects of microstripline discontinuities and bias circuits. Exposure of students to advanced CAD tools is necessary to equip them for the needs of local industry. One of the laboratory experiments involves the measurement of the complex scattering parameters of a field-effect transistor (FET) mounted in a microstrip test fixture, and the other, measurement of amplifier noise figure. For the first experiment, an economy vector network analyzer that operates up to 6 GHz is used. For the second experiment, a solid-state microwave noise-source, a preamplifier, and a spectrum analyzer (to measure noise power) are used.

It is apparent in EE4104 that microwave amplifiers is an important topic from the proportion of lecture hours (about one third of the course), the assignment, and the laboratory experiments. To this end, the closed-book examination, at the end of the course, has two questions devoted to microwave amplifiers. Normally, the class size consists of about 10 students, and at most, only one student fails EE4104. The low failure rate is attributed to the fact that EE4104 is an elective.

III. Approach to Teaching Microwave Amplifier Design

This section will describe in detail the treatment of microwave amplifiers in EE4104. Prospective EE4104 students are assumed to have knowledge and skills in transmission-line theory, Smith charts, and transmission-line-matching network design.

A. Normalized Waves and Scattering Parameters

The student often perceives normalized waves and scattering parameters as detached from the rest of electrical engineering. He or she needs to understand that normalized waves are just other ways, in addition to voltage and current, of looking at electrical phenomena and are consistent with familiar concepts, such as power transfer. The treatment, therefore, develops normalized waves from familiar concepts, such as transmission-line phenomena and power transfer between a generator and load. To eliminate unnecessary complication, the author presents the treatment for the special case of a pure-real reference impedance ($\mathrm{Z_o}$) that is sufficient for almost all applications that the student is likely to encounter.

Unless the EE4104 students have completed one of the other elective courses in the microwave/RF area, they will not have been exposed to two-port parameters. EE4104 is not designed to give a thorough treatment of two-port parameters but, rather, to extend the concepts of describing the terminal behavior of one-port elements to two-port elements. EE4104 students, therefore, see Z, Y, and S parameters in one shot by their defining terminal relationships between voltages and currents (involving Z and Y parameters) and waves (involving S parameters). Properties such as symmetry, losslessness, and reciprocity of two-port networks are not discussed in relation to microwave amplifiers but are discussed elsewhere in-depth in other microwave/RF elective modules.

B. Microwave Transistors

In a core electrical engineering course, the students have been taught the structure and operation of the bipolar junction transistor (BJT), the FET, and the metal–oxide–semiconductor FET (MOSFET), with emphasis on silicon devices. The purpose of EE4104 is to ensure the student has an appreciation of transistors (metal–semiconductor–field-effect transistor, high-electron mobility transistor, heterojunction bipolar transistor) used in microwave amplifiers, including basic operation, application, and biasing, as well as knowledge of commonly used semiconductors (GaAs, Si, SiGe), and future semiconductors (GaN, InP, SiC, Diamond) used for microwave transistors. Detailed device physics and device fabrication is beyond the scope of EE4104.

C. Nomenclature

The discussion of microwave amplifier theory and design centers round the archetypical, single-stage microwave amplifier schematic shown in Fig. 1. N1 and N2 are lossless impedance transformers that respectively transform the external generator and load to Γ_S and Γ_L and are usually frequency dependent. The transistor (in this case, a FET) is represented by its two-port S parameters: $\mathrm{S_{11}}$, $\mathrm{S_{12}}$, $\mathrm{S_{21}}$, and $\mathrm{S_{22}}$, where port 1 is the input (gate), and port 2 is the output (drain). The transistor S parameters are both frequency and bias dependent.

The input generator and load both have impedances equal to the reference impedance $\mathrm{Z_o}$. The amplifier input reflection coefficient is Γ_in, and its output reflection coefficient is Γ_out. The input and output reflection coefficients of the transistor are given, respectively, by

$$\Gamma_1 = \mathrm{S_{11}} + \frac{\mathrm{S_{12}S_{21}}\Gamma_\mathrm{L}}{1 - \mathrm{S_{22}}\Gamma_\mathrm{L}} \tag{1}$$

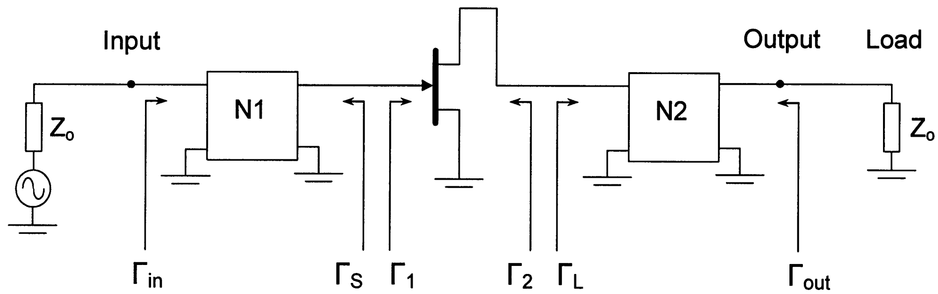

Fig. 1. Single-stage microwave amplifier schematic with bias circuits omitted.

and

$$\Gamma_2 = S_{22} + \frac{S_{12}S_{21}\Gamma_S}{1 - S_{11}\Gamma_S}. \tag{2}$$

Equation (1) is a bilinear mapping between the complex Γ_1 and Γ_L planes and, similarly, (2) is a bilinear mapping between the complex Γ_2 and Γ_S planes. The important observation is that the load is "felt" in the input circuit via (1) and the source is "felt" in the output circuit via (2) and is a consequence of the bilateral nature of the transistor (nonzero S_{12}). Authors of textbooks often use other nomenclature, and instructors should emphasize this point to students. For example, other authors may denote Γ_1 and Γ_2 as Γ_{in} and Γ_{out}, respectively.

D. Stability

Equations (1) and (2) are central to stability. It is possible that $|\Gamma_1|$ or $|\Gamma_2|$ can be greater than unity for certain passive values of Γ_L or Γ_S, respectively. When this possibility occurs, the circuit is considered unstable because a reflection coefficient whose magnitude is greater than unity corresponds to a negative resistance. This situation does not mean that the circuit will oscillate, since other conditions must be satisfied for such an occurrence.

A property of the bilinear mapping is that it maps circles into circles. The load stability circle

$$|\Gamma_L - C_L| = r_L \tag{3}$$

and the source stability circle

$$|\Gamma_S - C_S| = r_S \tag{4}$$

are described on the Γ_L and Γ_S complex planes, respectively. They are used to delineate allowable and forbidden values of Γ_L and Γ_S, respectively. The centers (C_L and C_S) and radii (r_L and r_S) of the stability circles can be derived from the circle mapping properties of (1) and (2) and are dependent solely on the transistor S parameters [5], [6]. The expressions for the center and radii are readily available in textbooks [5], [6] and are, therefore, not reproduced here. The exterior or interior of the stability circle is identified as the allowable region by considering the mapping of one convenient value of Γ_L or Γ_S—usually zero. Unconditional stability occurs when all passive values (within the unit circle) of Γ_L and Γ_S are allowable. Conditional stability is the case when only a fraction of all passive values of Γ_L or Γ_S are allowable. In EE4104, the author emphasizes the dual role of stability circles to identify the allowable regions and determine whether or not the transistor is unconditionally stable.

E. Mismatched Generator

To analyze microwave amplifier gain problems, one may consider power transfer between a generator with Thevenin impedance Z_A and a load Z_B. Z_A and Z_B need not equal the reference impedance Z_o, and, hence, the corresponding reflection coefficients Γ_A and Γ_B are in general nonzero. One can define a figure of merit—the mismatch factor M—being the proportion of the generator's available power delivered to the load. By circuit analysis using wave concepts, one can see that

$$M(\Gamma_A, \Gamma_B) = \frac{\left(1 - |\Gamma_A|^2\right)\left(1 - |\Gamma_B|^2\right)}{|1 - \Gamma_A\Gamma_B|^2}. \tag{5}$$

M is between 0 and 1 for a passive load with 1 corresponding to conjugate coupling of load to the generator. M may exceed unity (and could be infinite) for a negative resistance (or negative conductance) load.

F. Gain and Port Match

For the circuit shown in Fig. 1, one can define four powers: the power available from the generator P_A, the power delivered to the input of the transistor P_I, the power available at the output of the transistor P_O, and the power delivered to the load P_L. From these, one can define three useful gains, which are the available gain G_A, given by

$$G_A = \frac{P_O}{P_A} = \frac{|S_{21}|^2\left(1 - |\Gamma_S|^2\right)}{|1 - S_{11}\Gamma_S|^2 - |S_{22} - \Delta\Gamma_S|^2} \tag{6}$$

the power gain G_P, given by

$$G_P = \frac{P_L}{P_I} = \frac{|S_{21}|^2\left(1 - |\Gamma_L|^2\right)}{|1 - S_{22}\Gamma_L|^2 - |S_{11} - \Delta\Gamma_L|^2} \tag{7}$$

and the transducer gain G_T, given by

$$G_T = \frac{P_L}{P_A} = \frac{|S_{21}|^2\left(1 - |\Gamma_S|^2\right)\left(1 - |\Gamma_L|^2\right)}{\left|(1 - S_{11}\Gamma_S)(1 - S_{22}\Gamma_L) - S_{12}S_{21}\Gamma_S\Gamma_L\right|^2} \tag{8}$$

where Δ is equal to $S_{11}S_{22} - S_{12}S_{21}$. Note that G_A is a function of Γ_S, G_P is a function of Γ_L, and G_T is a function of both Γ_S and Γ_L. Another interesting result is G_T is related to G_A and G_P by

$$G_T(\Gamma_S, \Gamma_L) = G_A(\Gamma_S)M(\Gamma_2, \Gamma_L) = G_P(\Gamma_L)M(\Gamma_S, \Gamma_1). \tag{9}$$

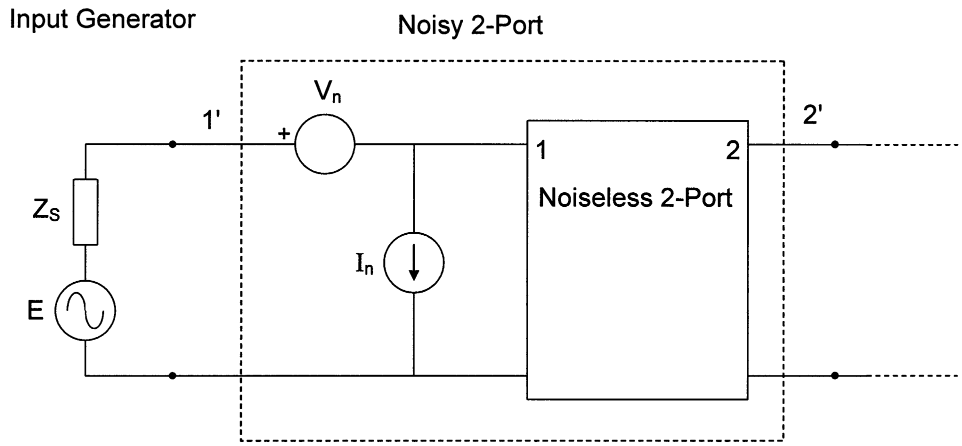

Fig. 2. Input generator and equivalent representation of a noisy two-port network.

The mismatch factor at both ports of a lossless network are identical. Applying this fact and (5) to the lossless networks N1 and N2

$$|\Gamma_{\rm in}| = \sqrt{1 - \frac{(1-|\Gamma_{\rm S}|^2)(1-|\Gamma_1|^2)}{|1-\Gamma_{\rm S}\Gamma_1|^2}} \quad (10)$$

and

$$|\Gamma_{\rm out}| = \sqrt{1 - \frac{(1-|\Gamma_2|^2)(1-|\Gamma_{\rm L}|^2)}{|1-\Gamma_2\Gamma_{\rm L}|^2}}. \quad (11)$$

This result implies that the choice of $\Gamma_{\rm S}$ and $\Gamma_{\rm L}$ dictate the magnitudes of $\Gamma_{\rm in}$ and $\Gamma_{\rm out}$ before N1 and N2 are realized.

G. Noise Figure

From a terminal-property point of view, a noisy two-port electronic device may be replaced by a noiseless version of the device, an equivalent noise current source $(\rm I_n)$ in shunt with the input, and an equivalent noise voltage source $(\rm V_n)$ in series with the input [6], as shown in Fig. 2.

The equivalent noise sources are described by their variance and correlation coefficient. One can see from Fig. 2 that the source impedance will effect the coupling of the noise power from the equivalent noise sources into the input port of the two-port, and hence, its noise figure. The function that describes the variation of the noise figure with $\Gamma_{\rm S}$ is

$$\rm F = F_{min} + \frac{4R_N|\Gamma_S - \Gamma_{Sopt}|^2}{Z_o(1-|\Gamma_S|^2)|1+\Gamma_{Sopt}|^2} \quad (12)$$

where $\rm R_N$ is the noise resistance, $\rm F_{min}$ is the minimum noise figure, and $\Gamma_{\rm Sopt}$ is the value of $\Gamma_{\rm S}$ where F equals $\rm F_{min}$. The noise parameters $\rm R_N$, $\rm F_{min}$, and $\Gamma_{\rm Sopt}$ are frequency and bias dependent. $\rm R_N$ is not a physical resistance but is a statistical parameter that happens to have the dimension of impedance and determines the steepness with which F increases with $\Gamma_{\rm S}$ about $\Gamma_{\rm Sopt}$. Students often ask why the load does not affect the noise figure. The answer to this question is that noise figure considers available powers for both signal and noise.

H. Gain and Noise Figure Circles

For a given transistor at a given bias point and frequency, the transistor S parameters are fixed, and, hence, the design variables are $\Gamma_{\rm S}$ and $\Gamma_{\rm L}$. From inspection of (6)–(8) and (10)–(12), one sees that contours of constant gain, noise figure, and mismatch are circles on the $\Gamma_{\rm S}$ or $\Gamma_{\rm L}$ planes , as the case may be. The centers and radii of these circles may be found in the various textbooks [1]–[6] and can be derived from the circle-mapping properties of bilinear transforms. Collin [1] presents an interesting discussion on gain circle properties and the relation to stability circles. One will normally only find unilateral gain, available gain, power gain, and noise figure circles. Circles of constant transducer gain (with either $\Gamma_{\rm S}$ or $\Gamma_{\rm L}$ held constant) are hard to find in textbooks but may easily be derived. To ascertain that the available gain or power gain circles have been correctly plotted for a conditionally stable transistor, one must to check that the family of circles intersect the unit circle at the same two points as does the source or load stability circle, respectively [1].

Students should note that one does not need to plot gain, noise figure, stability, and mismatch circles on a Smith chart, though several of the textbooks would have one believe that they should. Further, the scale of a Smith chart is typically too inconvenient for plotting load stability circles of a microwave transistor. (However, the Smith chart is still used in the design of impedance transformers N1 and N2.)

I. Low-Noise Amplifier Design

In low-noise amplifier (LNA) design, one should both maximize the gain and minimize the noise figure. Unfortunately, a minimum noise figure often yields an unacceptably low gain, or using simultaneous conjugate matching (for an unconditionally stable transistor) may yield an unacceptably high noise figure. Therefore, a compromise between noise figure and gain must be made. This compromise is aided by noise figure and gain circles. A flowchart summarizing the design steps is shown in Fig. 3.

Since noise figure F and available gain $\rm G_A$ are both dependent on $\Gamma_{\rm S}$, a suitable value of $\Gamma_{\rm S}$ is first chosen with the aid of available gain circles, noise figure circles, and the source stability circle plotted on the $\Gamma_{\rm S}$ plane. The idea is to select a point on the $\Gamma_{\rm S}$ plane that is allowable, offers high $\rm G_A$ and low F, and leaves an adequate safety margin with respect to the source stability circle. The success of tradeoff of F for increased $\rm G_A$

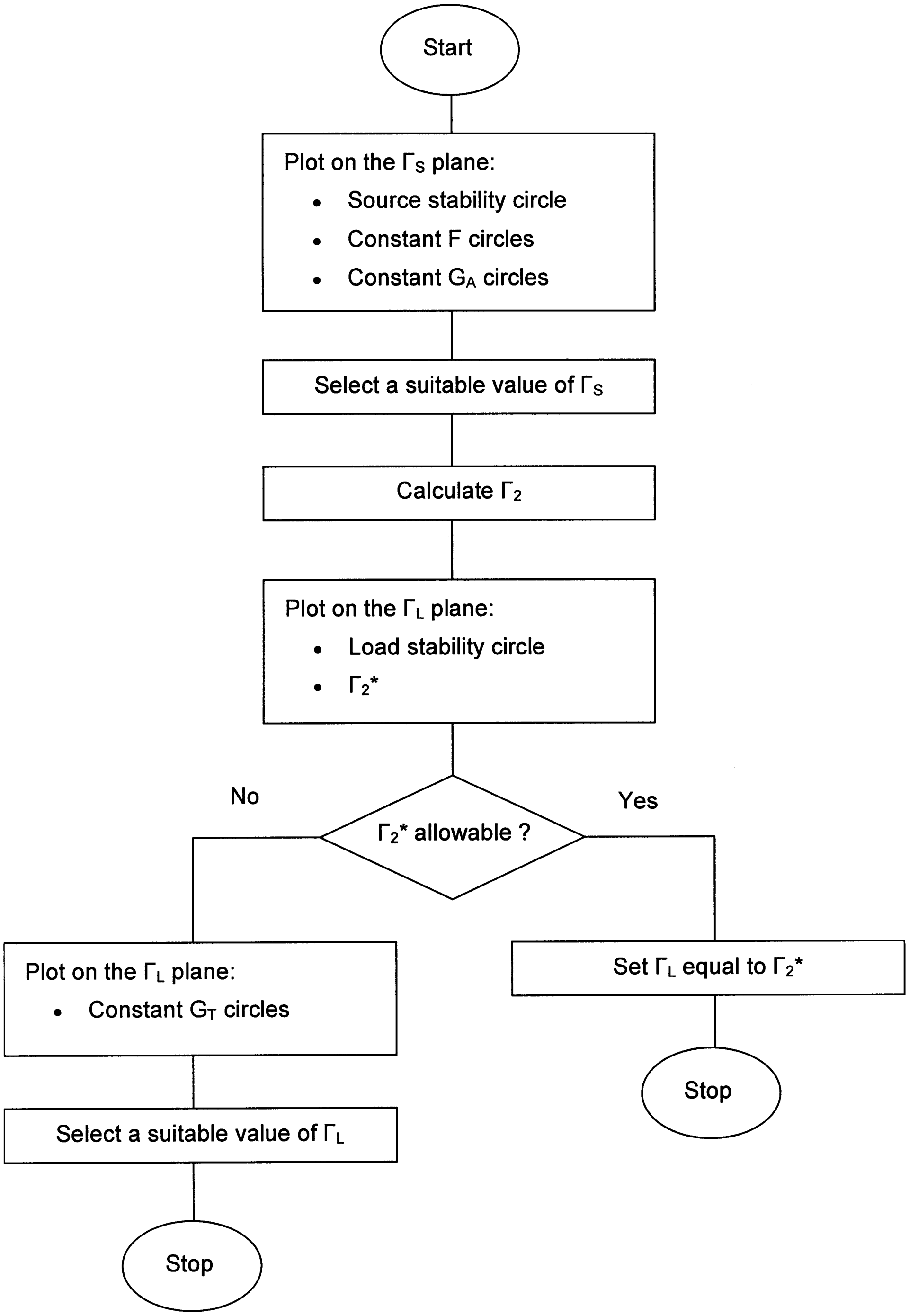

Fig. 3. Flowchart for LNA design.

is a result of the typically low sensitivity of F to Γ_S compared with G_A to Γ_S.

Having chosen Γ_S, Γ_2 can be calculated. The next step is to see if conjugate matching can be used at the output (i.e., Γ_L equal to Γ_2^*). This step is aided by the load stability circle described on the Γ_L plane. If conjugate matching cannot be achieved at the output, then constant G_T circles (with Γ_S equal to that chosen) must be plotted on the Γ_L plane, or equivalently, circles of constant output mismatch [1] plotted on the Γ_L plane can be used. However, under most circumstances, sufficient margin between Γ_S and the source stability circle ensures conjugate matching can be used at the output. Whatever method is used to select Γ_L, a sufficient margin must be maintained with respect to the load stability circle.

J. Impedance Transformer Design

An EE4104 student will be familiar with single-stub matching taught in a second-year module. In this case, an arbitrary impedance is transformed to the conjugate of the generator impedance. In amplifier design, one is concerned with the general problem of transforming an arbitrary impedance to another arbitrary impedance, e.g., transforming the external

50-Ω generator and load impedance to the desired value of $\Gamma_{\rm S}$ or $\Gamma_{\rm L}$, respectively. This problem is *not* a matching one, and this point has to be reinforced to the students; otherwise, they may design a stub whose susceptance has the incorrect sign. In EE4104, the author teaches design methods that locate the stub away from the ports of the transformer so that the transistor does not physically interfere with the stub.

K. Two-Stage Design

For two-stage amplifier design, the first step is to select source and load reflection coefficients for both transistors. The algorithm for single-stage LNA design (Fig. 3) can be used for the first stage. The complimentary algorithm to that shown in Fig. 3, where $\Gamma_{\rm L}$ is first selected followed by selection of $\Gamma_{\rm S}$, can be used for the second stage.

Designing the stub impedance transformers to realize $\Gamma_{\rm S}$ for the first stage and $\Gamma_{\rm L}$ for the second stage is straightforward. On the other hand, the network that couples the two transistors needs to achieve arbitrary impedance transformations in both directions. However, in general, a lossless coupling network can only be designed to achieve a desired transformation in one direction, unless the stages are conjugately coupled. Therefore, for ease of design, conjugate coupling may be used between each stage; hence, $\Gamma_{\rm S}$ is chosen for the first stage so that conjugate matching can be used at its output, and $\Gamma_{\rm L}$ is chosen for the second stage so that conjugate matching can be used at its input. Failing conjugate coupling, iteration involving reselection of $\Gamma_{\rm S}$ and $\Gamma_{\rm L}$ for each transistor, and design of the coupling networks, will usually be required to ensure that both stability and gain concerns are adequately addressed. Moreover, multistage amplifier design is easiest when unconditionally stable transistors are used for the second stage up to the stage before the last. Because of the limited teaching time available in EE4104, the author adopts the approach using conjugate interstage coupling.

IV. Discussion

Section III has described the essential features of the narrow-band microwave amplifier analysis and design methods taught by the author in EE4104 at the NUS. The following is a discussion of a number of issues that are considered.

The design method of Section III primarily focuses on the center frequency; however, stability must be satisfied at all frequencies. The design must be checked by circuit simulation to ensure that input and output reflection coefficients (for example) have magnitudes less than unity at all frequencies. The low-frequency regime is an area that needs close attention where transistors are highly prone to oscillation. Bias circuitry is particularly problematic, and carelessly designed bias circuitry is often the cause of amplifier oscillation in practice.

This author briefly discusses how the well-known K stability factor is derived from the stability circles and shows why, for certain cases, K greater than unity (and $|{\rm S}_{11}|$ and $|{\rm S}_{22}|$ less than unity) is insufficient on its own to conclude absolute stability. These special cases lead to the extra conditions that must be satisfied [1]–[6]. Another recent advance, well worth noting to students, is the so-called μ stability factor [9].

The ability to achieve conjugate match at one port (e.g., the output of a single-stage LNA) of a conditionally stable transistor is dependent on the choice of the first termination (e.g., $\Gamma_{\rm S}$ for the single-stage LNA). If unsuccessful on the first attempt, then the first termination will have to be moved away from its stability circle. Edwards *et al.* [10] have shown that the maximum available or power gain for which conjugate matching can be obtained at the output or input port, respectively, is $2\,{\rm K}|{\rm S}_{21}/{\rm S}_{12}|$. This formula is useful, but the student should also observe the effect of moving the first termination with respect to its stability circle.

One of the problems associated with designing amplifiers with conditionally stable transistors, where one of the ports is conjugately matched and the other is not, is that the unmatched port is often severely mismatched. One can trade off the match between the two ports with the aid of a constant mismatch or voltage standing wave ratio (VSWR) circles [1], [5], [6]. Alternatively, a numerical method [11] can be used to optimize the port match of a low-noise amplifier. However, because of a limited amount of teaching time, the author only gives a brief demonstration of the benefit that can be achieved by trading off port match.

The students of EE4104 use advanced microwave CAD software to simulate their LNA design. For some of them, this experience will be their first exposure to such tools, and to assist them getting started, this author has prepared a two-page guide on circuit entry and small-signal S parameter simulation in Agilent ADS [7]. All students are able to learn quickly the skills necessary to perform the S parameter simulations required for their assignment.

Many microwave amplifier design calculations involve straightforward but tedious complex arithmetic. An exam paper needs to focus on assessing the students' skills and knowledge in relation to the course objectives. This focus cannot be achieved if the examination requires the student to perform lengthy complex arithmetic. The approach that the author has used when setting examinations is to provide precalculated values of centers and radii of stability circles, and gain and noise figure circles for three or four values of gain and noise figure. At most, the student may only have to perform calculation of Γ_1 or Γ_2. In two-stage amplifier design questions, the transistor S parameters are often chosen so that $|{\rm S}_{11}|$ and $|{\rm S}_{22}|$ are equal, resulting in identical source and load stability circles, and available gain and power gain circles, apart from an angular displacement.

V. Conclusion

In this paper, the author has described a method by which to teach students the design of narrow-band low-noise amplifiers, both single-stage and multistage, using conditionally stable transistors, in 9 h of lectures and 2 h of tutorials. To achieve this goal, the unilateral case is not discussed, and the dual role of stability circles is emphasized. This approach has been used successfully by the author for nearly ten years. A design and simulation assignment is used to reinforce the design methods and demonstrate the behavior of the amplifier.

ACKNOWLEDGMENT

This author would like to thank Prof. P. S. Kooi, the National University of Singapore (NUS), and Prof. S. Uysal, Eastern Mediterranean University, with whom the author has had the pleasure of sharing the teaching of EE4104 and who have provided excellent moderation of his exam questions. The author also would like to thank past students of EE4104 whose perceptions have led to improved ways of presenting the lectures and tutorials on microwave amplifiers. The author would also like to thank Prof. M. S. Leong, NUS, for his suggestions that have contributed to the quality of EE4104 and for his encouragement to disseminate my teaching methods in this domain. Finally, the author wishes to thank the reviewers of this paper for their invaluable suggestions.

REFERENCES

[1] R. E. Collin, *Foundations for Microwave Engineering*, 2nd ed. New York: McGraw-Hill, 1992.
[2] R. S. Elliott, *An Introduction to Guided Waves and Microwave Circuits*. Englewood Cliffs, NJ: Prentice-Hall, 1993.
[3] J. Helszajn, *Microwave Engineering: Passive, Active and Non-Reciprocal Circuits*. New York: McGraw-Hill, 1992.
[4] D. M. Pozar, *Microwave Engineering*, 2nd ed. New York: Wiley, 1998.
[5] T. T. Ha, *Solid-State Microwave Amplifier Design*. New York: Wiley, 1981.
[6] G. Gonzalez, *Microwave Transistor Amplifiers: Analysis and Design*, 2nd ed. Upper Saddle River, NJ: Prentice-Hall, 1997.
[7] Advanced Design System (ADS) (2002, Dec.). *Available: http://www.agilent.com* [Online]
[8] Serenade Student Version 8.5 (2002, Dec.). *Available: http://www.ansoft.com* [Online]
[9] M. L. Edwards and J. H. Sinsky, "A new criterion for linear 2-port stability using a single geometrically derived parameter," *IEEE Trans. Microwave Theory Tech.*, vol. 40, pp. 2303–2311, Dec. 1992.
[10] M. L. Edwards, S. Cheng, and J. H. Sinsky, "A deterministic approach for designing conditionally stable amplifiers," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 1567–1575, July 1995.
[11] K. W. Eccleston, "Port-match optimization of microwave low-noise amplifiers," *Microwave Optical Technol. Let.*, vol. 27, no. 5, pp. 321–323, Dec. 5, 2000.

Kimberley W. Eccleston (S'85–M'90) was born in Melbourne, Australia, in 1964. He received the B.E. degree in electronic engineering with distinction from the Royal Melbourne Institute of Technology (RMIT), Melbourne, Australia, in 1986 and the Ph.D. degree from the University of Queensland, Brisbane, Australia, in 1991.

From 1990 to 1992, he was a Research Scientist with the Defence Science and Technology Organization, Adelaide, Australia. Since 1992, he has been with the Department of Electrical and Computer Engineering, National University of Singapore (NUS), where he is currently a Senior Lecturer. He has taught students at various levels and has developed specialized courses in microwave active circuit design at both the undergraduate and graduate levels. His research currently focuses on active and passive microwave circuit design. He has had experience in microwave measurements and microwave device modeling, and he has authored more than 40 technical papers and has been granted one patent.

Dr. Eccleston has been a key member of organizing committees of several IEEE conferences hosted in Singapore.