CHAPTER - I
1.0 INTRODUCTION

Well performance in wide-ranging thermal environment is always demanded from airborne and space-based microwave electronic circuits and systems. The success of electronic system for these applications relies on the ability to design high performance, high reliable circuits which function in demanding thermal environments. To accomplish this, designers require greater understanding about the temperature behavior of microwave devices and circuits. However, the temperature-behavior of microwave semiconductor devices and circuits has received little attention even though under certain conditions effects can be severe.

Performance parameter of microwave diodes and transistors changes with temperature. Attenuation and phase shift of PIN diode based microwave circuits and limiting power level, attenuation & phase shift of Schottky barrier diode based circuits are all functions of temperature. Gain, saturated output power and nonlinear parameters of GaAs FETs and HEMTs are also changes with temperature.

PIN diode and Schottky barrier diodes are popularly used in various microwave circuits and systems such as power limiter, variable attenuator, phase shifter, linearizer, automatic level control system, etc.

PIN diodes have been used for several decades [1] - [7]. This device used for attenuator, phase shifter and limiter from microwatt to megawatt level [7] of power at the frequency range of RF, microwave and extended to mm wave range. Though silicon PIN diodes are more popularly used, GaAs PIN diodes are also available for fast switching applications [8]. GaAs PIN diodes are more suitable to operate at mm wave frequency range.

Although extensive work has been done for accurate modeling of the PIN diode to design high frequency circuits for high power applications [9] - [11], the design of bias
networks for electronically controlled PIN diode based attenuators, phase shifters, etc. has remained something of a black art. This is particularly true when accurate control is required over a wide operating temperature range. The reason is that the effect of temperature on the RF resistance of PIN diodes was not well understood in the past. In the early 1980s, Alfa industries Application Note No. 80200 [2] had this to say: "We do not label the [Temperature versus RF resistance] curves because we do not yet have enough data and do not want to mislead you. We want you to realize that you will have to do your own experimenting with your diode in your application." Indeed, it was not until 1993 that Caverly and Hiller [12] - [14] showed that the RF resistance of these diodes varies as the \((2-m)\)-th power of the temperature, where the power \("m"\) lies between 0 and 2 for practical PIN diodes. Caverly and Hiller have suggested using specially fabricated PIN diode of \(m = 2\), to achieve temperature insensitive PIN diode attenuation [14]. However, this technique is not applicable to large varieties of commercially available microwave PIN diodes for which \(m \neq 2\). Moreover, the PIN diodes of \(m = 2\), have very high parasitic capacitance values for oxide passivation and not workable for high range of attenuation at microwave frequency range [12] - [13]. Therefore, suitable temperature compensation circuit is required to achieve temperature invariant RF performance of PIN diode based RF circuits.

There are numerous temperature compensation mechanisms for PIN diode based circuits [15] - [20]. All the conventional compensation circuit uses temperature sensor to sense the temperature of the diode and produce a signal that is function of temperature. Among the various compensation mechanisms, some of the compensation mechanism based entirely on analog control signal [15] - [18], while others contain digital devices acting at discrete temperature steps [19], [20]. The entire conventional temperature compensation schemes using temperature sensor having their own disadvantages of compensation errors due to self-heating of the diodes when they are operated under high power condition.

Some analog compensation circuit used thermistor [15], [16] as the temperature sensing elements and other uses diode [17] as the temperature sensor. Analog compensation circuit sense the ambient temperature of the diodes and produce temperature dependent control signal. Change of thermistor’s resistance and change of diode’s voltage drop with the change of temperature produces temperature dependent
control signal. In case of analog compensation circuits, temperature dependent control signal controls diode current continually over the ambient temperature to provide temperature invariant performance. Some analog compensation circuits are simple, consisting with only resistive networks with their less accurate performance whereas some circuits [18] are complicated containing several amplifiers and comparators to provide performance that is more accurate. Moreover, circuit complexity increases when many number of step attenuation is required.

Digital compensation circuits also use same type of temperature sensors as used for analog compensation circuits. Some digital compensation circuit uses ADC/DAC combination [19] whereas other circuit uses microprocessor based control [20]. Digital control circuits are more accurate but require more number of components and time consuming for setting. Microprocessor based compensation circuit [20] uses look-up tables. With the variation of ambient temperature address of the memory changes and predetermined data from memory produces control voltage for PIN diode based circuits to provide temperature invariant performance. Main drawback of the digital compensation circuit is that the performance of the circuit controlled in a stepwise fashion, means produce oscillation for digital quantization.

The thesis work investigated the consequences of the temperature behavior of PIN diodes by designing several PIN diodes based circuits [21] - [24] and proposed a novel compensation technique to achieve temperature insensitive RF performance. It is shown that the proposed compensation scheme, based on the novel optimum bias load line technology, can provide a setting accuracy of 0.2 dB over a very wide temperature range of −20 to +70 °C for all practical PIN diodes. The proposed scheme achieved temperature insensitive RF performance of PIN diode based circuits without using any temperature sensor or separate compensating mechanism, but responds directly to the junction temperature of the diodes. This prevents any errors caused by temperature gradients, or by self-heating of the diodes due to operation at high RF power level.

Schottky barrier diodes are widely used for microwave applications [26], [27]. This device is used as RF detector, attenuator, mixer, limiter, etc. Among the various types of linearizers [28] - [41], Schottky diode based linearizers are gaining popularity due to their low power consumption, compact size, and ease of operation. Schottky diode is used to generate non-linear characteristic for linearizer applications [28] - [39] and also
are used as microwave phase shifter for microwave beam forming network. Cut-in voltage and RF resistance of the Schottky barrier diode is known to vary with temperature. Thus, attenuation, limiting power level, non-linear characteristic and phase shift of Schottky diode based circuits will change with temperature.

Some Schottky diode based linearizers are series [28], [29] diode based circuit and others are parallel diode based circuits [30], [31]. Series diode based linearizer circuits are biased by nearly constant voltage source whereas parallel diode based linearizers are biased by nearly constant current source to achieve proper amplitude and phase characteristic of the linearizer to linearize nonlinear characteristics of SSPA and TWTA. Under constant voltage or constant current bias condition, Schottky diode based linearizer’s performance changes with temperature since RF resistance of the diode is function of temperature. The circuits where diodes are biases with constant voltage bias condition will be suffered severely with change of temperature whereas constant current biased diode circuits will be less affected.

Although constant voltage or constant current biased Schottky diode based circuit’s performance affected over the change of temperature, surprisingly there is no open report addressing this effect. However, same temperature compensation mechanisms applicable for PIN diode based circuits are also can be applicable to compensate Schottky diode based circuits with their merits and demerits. The thesis work proposed and successfully demonstrate that the “optimum bias load line technology” applicable for temperature compensation of PIN diode based circuits are also applicable for temperature invariant performance of Schottky barrier diode based circuits with their merits of simplicity, compactness and ease of operation and no error due to self heating of the diode [21], [41].

The thesis work extended the proposed temperature compensation scheme “optimum bias load line technology” used for PIN diode and Schottky barrier diode based circuits, used for temperature compensation of output light intensity (brightness / illumination) variation of Light Emitting Diode (LED). Today, LEDs are used widely for domestic lighting and for signal lighting in automobile applications. LEDs are also used as reference source for colour printer and measuring instruments [42], [43]. Light intensity of LED decrease exponentially with the increase of diode temperature [43]. Thus for solid state lighting application, LEDs light becomes dimmest during hot summer day and
brightest during cold winter day which are contrary with the requirement. In colour printer and instrument applications, where it is used as reference light source, intensity variation creates change of colour and measurement errors respectively. There are various temperature compensation mechanisms, which are based on ambient temperature sensor [43] – [46], with their demerits of circuit complication and compensation error due to self-heating of the diode. The thesis work [47], [48] proposed and successfully demonstrated theoretically and practically that “optimum bias load line technology” can provide temperature invariant light intensity of LEDs with its merit of simple circuit and no error due to self-heating of the diode.

Microwave transistors such as MEtal Semiconductor Field Effect Transistors (MESFETs), and pseudo-morphic High Electron Mobility Transistors (pHEMTs) play an important role in microwave applications [49]-[52]. These devices are becoming more prevalent as the demand grows for high-speed data transfer and internet access. As a result, users are demanding smarter circuits with temperature insensitive performance for the present systems.

Several researcher conducted extensive research about temperature behavior on MESFET and HEMT devices [53] – [56]. DC performance [53] as well as RF performance [54] – [56] of MESFET and HEMTs is changes with temperature. Linear gain, saturated output power level, and efficiency of GaAs-based FETs depend strongly on temperature [52]. At fixed drain current and voltage bias, transconductance \( g_m \) as well as FET unity current gain cut-off frequency \( f_t \) decreases with increasing temperature. Therefore, in case of fixed drain current bias, small signal gain, saturated output power level and efficiency of the amplifier decreases with increasing temperature. It has been known from the equivalent circuit model and verified by the experiments on various amplifier circuits [57] that the linear gain of GaAs-based FETs and HEMTs decreases approximately by 0.015 dB/°C for each stage as the channel temperature increases. Thus, FET gain tends to decrease greatly with temperature, even for FETs biased at a constant current bias. Such a decrease will significantly degrade the system performance.

Decrease of small signal gain and output power level with the increase of device temperature is the main concern for microwave amplifiers. There are various methods to compensate small signal gain variation of MESFET and HEMTs [58] – [61]. Some
temperature compensation technology includes on-chip compensation mechanisms [58], [59] and other technology uses separate variable gain blocks in the amplifier line up to compensate overall performance. The thesis work demonstrates [61], [83] temperature compensation mechanism using variable PIN diode attenuator to compensate overall gain variation of the amplifier.

There are various microwave subsystems based on PIN diode, Schottky barrier diode, MESFET and HEMTs [62] – [83] used for satellite and other applications. In the thesis work temperature behavior and compensation of various spacecraft subsystems, such as, PIN diode based beam forming network [70], [71] diode based linearizer [39], [40] over drive level control system for SSPAs [80] and Ku-band channel amplifier with automatic level control system [83] are discussed. These subsystems are designed using GaAs FET and HEMT devices, PIN diodes and Schottky barrier diodes. Temperature compensation schemes of the subsystems are proposed, mathematical and practical procedures are given to determine the component values. These subsystems are characterized over operating temperature range and test results are presented.
1.1 STATEMENT OF PROBLEM

One of the intent of the research is proper understanding of temperature behavior of microwave semiconductor devices such as PIN diode, Schottky barrier diodes and GaAs based MESFET and HEMTs. Another intent of the research is to explored the temperature compensation mechanisms for various microwave circuits and systems, based on semiconductor active devices, suitable for high reliable air borne and space based application.

The temperature behavior and compensation mechanisms, suitable for airborne and space-based microwave active circuits and systems, addressed in the present research work are categorized as below:

- Circuits based on RF resistance of microwave diodes such as PIN diode and Schottky barrier diode.
- Circuits based on pHEMT and MESFET devices.
- Complete subsystems based on various microwave diodes and transistors.
1.2 Organization of Thesis

The thesis is organized in five chapters addressing temperature behavior and compensation mechanisms of different microwave diodes and transistors. Popularly used microwave diodes used for satellite microwave communications are PIN diode and Schottky barrier diode. A novel technique is invented for temperature compensation of these microwave diodes. It is also presented that the same technique is also applicable to the temperature compensate of output light intensity of light emitting diode. Among the microwave transistors temperature behavior of GaAs MESFET and pHEMT are addressed. At last design development, temperature characterization and compensation techniques of various microwave circuits and subsystems based on solid-state active devices are also presented.

Chapter-I consists of introduction containing literature survey and statement of the problems addressed in the thesis.

Chapter-II addresses temperature behavior and compensation technique of various junction diodes. Different temperature compensation techniques of RF resistance of PIN diode and Schottky barrier diodes are discussed and a novel technique is proposed to achieve temperature insensitive RF resistance, which leads to temperature invariant attenuation of diode based RF circuits. Here it is investigated the consequences of the temperature behavior of PIN diodes by designing several PIN diode based circuits and proposed a simple technique to achieve temperature insensitive RF performance. It is shown that the proposed temperature compensation technique, based on the novel optimum bias load line technology, can provide an attenuation setting accuracy of 0.2 dB over a very wide temperature range of –20 to +70 °C for all practical PIN diodes. Different circuits operating at frequencies S, C and Ku-bands are realized with the optimum bias load line scheme using different types of PIN diodes. It is verified that the proposed load line biasing scheme provide nearly temperature invariant RF resistance for all practical available PIN diodes at all the operating frequency range. This temperature insensitive RF resistance is achieved without using any temperature sensor or separate compensating mechanism, but responds directly to the junction temperature of the diodes. This prevents any errors caused by temperature gradients, or by self-heating of the diodes due to operation at high RF power level.
The thesis work offers a fresh look into the temperature behavior and compensation mechanism of Schottky barrier diode at radio frequency operation by designing various Schottky barrier diode based circuits. Here it is shown that, temperature invariant RF resistance of Schottky diode can be achieved by proper selection of the bias load line. Thus, without any separate temperature sensor and compensation circuits, as used in conventional temperature-compensation scheme, it is possible to achieve temperature compensated RF resistance of Schottky diode. Mathematically it is shown, and verified by the measurements that, variation of RF resistance, which is nearly 24% in case of fixed current bias over the operating temperature range of -10 to +60 °C, can be minimized to nearly zero by the proposed optimum load line biasing scheme. Temperature characterization and compensation of Schottky barrier diodes performance over varying RF power level is also presented.

The temperature compensation scheme used to compensate PIN and Schottky barrier diode is extended for temperature compensation of output light intensity (brightness/illumination) variation of Light Emitting Diode (LED). Light intensity of LED decreases with increase of diode temperature at fixed current bias condition. Today, LEDs are used widely for signal lighting in automobile applications. During hot summer day at noon, LEDs light becomes dimmest contrary with the requirement of brightest intensity, and during cold winter day at night, LEDs light becomes brightest contrary to the requirement of dimmest intensity. In color printer application, light intensity fluctuation results in a change of color. In the measuring instrument application, where it is used as a reference intensity light source, intensity variation creates measurement errors. In the research work, temperature behavior of light-emitting diode’s parameters investigated mathematically and exploited the temperature variation of diode current to improve the temperature dependency of LED’s light intensity. It is shown, that the equiintensity curves of LEDs can be considered as nearly a straight line over the operating range of diode temperature. Therefore, by selecting the best-fitted load line along the equiintensity curve leads to nearly temperature invariant light intensity. Test results confirms the same and verified by the measurements that, peak to peak variation of light intensity, which is nearly 99% in case of conventional constant current bias, over the temperature range of -20 to +80 °C, can be minimized to nearly 6% by selecting proposed optimum load line biasing scheme.
Chapter-III addresses temperature behavior of GaAs based MESFET and HEMTs. Through different experiments, it is shown that linear gain of GaAs-based FETs and HEMTs decreases approximately by 0.015 dB/°C for each stage as channel temperature increases. Also discusses different techniques for temperature compensation of gain and output power variation.

Chapter-IV addresses temperature behavior of some microwave subsystems. In this work, temperature behavior and compensation of various spacecraft subsystems, such as, PIN diode based beam forming network, diode based linearizer, over drive level control system for SSPAs and Ku-band channel amplifier with automatic level control system are discussed. These subsystems are designed using GaAs FET and HEMT devices, PIN diodes and Schottky barrier diodes. Temperature compensation schemes of the subsystems are proposed, mathematical and practical procedures are given to determine the component values. These subsystems are characterized over operating temperature range and test results are presented.

Chapter-V contains summary conclusion and future scope.