Methodologies for achieving High Reliability in Microwave Electronics Design

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Abstract. The design of any microwave device depends upon the careful selection of individual components and their assembly ensuring a highly stable operation. Modelling the microwave device characteristics throughout its life cycle also enables an assessment of its reliability.

Modern commercial electronics are normally designed to reduce cost. For aerospace and defence applications however, microwave electronics are designed for high performance and reliability, which always compromises cost. To reduce the production costs whilst ensuring good reliability is a delicate trade-off. Incorporating this into design procedures has been explored.

1. Introduction

It is essential for a microwave electronics manufacturer to produce components that have high quality and good reliability in order to maintain their customer base and reputation; quality and reliability are indeed very important attributes for success in high technology markets [1].

Design for reliability must therefore be integrated into the design methodology from the very beginning of the entire product design process, to prevent any reliability issues arising at any stage in the design process. It also enables fewer design changes and iterations, resulting in reduced long-term costs. Product returns will be minimised, reducing warranty and service cost. Generally, a financially successful manufacturing company that maintains good reputation with its customers relies on a design-for-reliability approach to be fully integrated into the methodology [2].

2. Design Methodologies for Reliability: Design, Modelling and Manufacture

When an initial design concept is proposed a reliability prediction model provides the feasibility of the reliability of a component or system. It is necessary at this early stage to carry out reliability predictions as they can direct the product design decisions from the initial stage and can be critical to the success of its development. The initial feasibility study is often based on the limited design information gained at the early stage which will give an approximate prediction. An example of this is given in section 3. .

As the design is progressed decisions will be reached on various alternatives. Product performance and cost will play a major consideration and these are weighted up against its reliability. The reliability information at this stage will identify the parts or part groups that are the high contributors to failure rates. Alternative redesigned layouts and/or alternative parts are suggested at this stage to improve its performance (i.e. functional performance: gain and low noise, reliability, cost, size, weight etc.). For military standard type components, the emphases are on functional performance and reliability whilst maintaining acceptable cost. For space applications, the reliability factor has even greater emphases and weight becomes a critical factor [3].

For the design of high reliability microwave components it is recommended to use a reliability software prediction model as it will take complex factors into consideration that are different and tedious to model analytically e.g. stress levels that the components are subjected to whilst in long-term operation. For military type predictions the "MIL-HDBK-217" [4] model was used as a basis for reliability predictions. This handbook contains failure rate models for the various part types used in electronic systems, such as capacitors, inductors, resistors, switches, ICs and transistors etc. Accurate failure rate models are created from these components for a wide variety of electronic parts and systems, which are connected in series or in parallel.

Use of this model at Telcordia (formerly Bell Communications Research) found that it over exaggerated the failure rates for the commercial quality products at this company and, consequently, adapted the model for commercial-type products [5]. This modified model became known as "Telcordia SR-332".

Both, MIL-HDBK-217 and Telcordia SR-332 have been developed to automate and run as a software application for Windows e.g. "RelCalc for Windows" [6] or Relax Reliability Prediction [7]. User friendly programs, such as these, allow the mean time between failures of electronic components to be predicted to good accuracy; and are also backed up by analytical estimates of the reliability and a prediction of the failure rates. The design and manufacturing methodologies of high reliability microwave components include: the selection of materials and chip devices, design and manufacturing procedures with consideration for its operation conditions. All of these aspects will now be discussed.

2.1 Component and Material Selection

Design of microwave devices usually starts from the drawing process using design software packages. For design for high reliability, however, emphasis is placed on component selection at the initial stage as there are few specialist parts build for high reliability. Manufacturers of such parts include large semiconductor companies such as: Infineon and Microsemi, good quality materials are used e.g. GaN, Si, SiGe, SiC, GaAs and they are normally categorised separately under "Hi-Rel" products.

These highly reliable components are to be carefully bonded onto a quality substrate e.g. Alumina to produce a working board. The best quality materials for a substrate are therefore chosen.

2.2 Computation Design for High Reliability

Once the choices of components are known then the specialist microwave design packages can be used to design the layout and simulate its behavioural properties. The high quality design packages for microwave components are supplied by the companies of Agilent, AWR and Ansoft.

With microwave electronics, many of the chip components can be replaced with microstrip components, e.g. thin film resistors to replace chip resistors, microstrip gaps to replace chip capacitors and printed spirals to replace chip inductors. However, this approach has physical limitations with the parameter values of these devices, particularly with the range of capacitance achieved with gaps, so therefore, single or multi-layer capacitors would be bonded onto the substrate instead. The active solid-state components (bipolar transistors, FETs, chips etc.) are the least reliable devices on a microwave circuit board, which is mainly due to their higher complexity [4]. Printing these devices on a board would be very difficult, due to their complexity, nowadays, it is more practical to buy-in these parts from the Hi-Rel suppliers.

2.3 Manufacturing Procedures

The manufacturing processes for high quality and reliability are done more carefully and precisely than standard processes. A high temperature eutectic hard solder e.g. Au/Sn is more preferable instead of any soft solder (Pb/Sn), as this will eliminate solder creep and re-crystallisation [8]. The eutectic die bonding methods use more expensive type materials and the heating and cooling process takes longer. The processes for bonding wires onto the bare die to link the components together need to be done to ensure a robust joint, the wires themselves need to be doubled or tripled to minimise the chance of open circuit or electrical disconnections under mechanical stress.

Generally, high quality materials are chosen to prevent the long-term wear-out effects of fatigue, creep and corrosion and the manufacturing processes must be robust to prevent wear and tear of long-term usage. As these high quality materials, robust bonds and multiple connections are used the cost of production and labour are increased.

Design for reliability also requires additional/improved technology to maintain the regulation of the power supply and other environmental conditions. These variables that affect the reliability of components will now be discussed along with the design and manufacturing procedures required to overcome these conditions.

2.4 Voltage Regulation

All active microwave components are powered by a voltage supply, which can contain fluctuations. A major cause of component failures arise from surges in the power supply voltage or incorrectly applied voltage particularly during the initial stage of its operation. In order to prevent this from occurring it is essential that any supply of ac or dc voltage is properly regulated and any multiple voltage and current surges are correctly handled. The supply would therefore include voltage regulators possibly containing a TVS (Transient Voltage Suppression) circuit. Basic, low cost, microwave components would not include all of this extra circuitry, this would only be found in products where reliability is a strong requirement i.e. defence or space use. All of this extra circuitry, of course, adds to the cost of design and manufacture often increasing the price by a multiple of times.

2.5 Thermal Regulation

For a reliable design, it is desirable to have maximum thermal conductivity throughout the circuit so that the most amount of heat is dissipated. This ensures that the temperature regulation of the circuit is maximised thus preventing any likelihood of overheating. Alumina is often used as a substrate which has good thermal conductivity; this effectively dissipates the heat generated by the semiconductor devices. A well designed circuit will also ensure that the devices are adequately separated from each other to prevent overheating. In some applications, the methods of radiating the heat away from components are also a major part of the overall design. Radiator fins with a high thermal conductivity are often used for this purpose. All other aspects of the circuit layout are designed to minimise thermal resistance and to withstand high thermal cycling.

2.6 Environmental Regulation

It is strongly preferred to package the electronic devices and components in hermetic packaging, for example GelPack or Micro-X, to ensure no water vapour or other contaminants enter the circuitry. For space and military applications the circuitry must also be protected against vibration and mechanical shock as well as changes in air pressure and temperature. The design layout and circuit devices are specially designed to handle the extremes of these conditions. Additional pre-cap inspections and tests are required before the protective enclosure is sealed.

2.7 Conclusions: Design and Manufacturing for Reliability

In this section, many of the design and manufacturing considerations and procedures have been discussed. To summarise: components that are built for reliability require the technology to be radically different to those that are designed for cost. With the additional circuitry for power supply regulation, more sophisticated eutectic bonding methods, hermetic type packaging, additional connections and more inspections etc., the overall cost of production and labour are many times that for a commercial product. For defence, space and aerospace applications however, the benefits of greater reliability however out-weight this increased spending.

A method of reducing cost whilst maintaining high reliability is to design one complete component package which will contain the technology for a long-term reliable performance, whilst simplifying the design as much as possible. This simplicity may involve: fewer voltage regulators in a unit, fewer amplifier stages (but with higher gain in each), a redesigned board layout containing the minimum number of bare die. The electronics of the components can also be redesigned so that a slight deviation in the parameters values, e.g. capacitance, will have a lesser consequence on its performance. Any slight changes in the component values, caused by environmental conditions or prolonged use, would therefore have less affect on its performance.

3 Analytical Prediction Models

In order to model the reliability of the system (containing a network of electronic devices) the failure rates of all the different parts are required. Information about the product's reliability is obtained from its operational life testing which involves power cycling, electrical and thermal stressing. This reliability information can be obtained directly from the manufacturer and from the prediction model containing this reliability data (e.g. "MIL-HDBK-217", see section 2).

As an example, let us assume that a simple VCO (Voltage Controlled Oscillator) contains 30 parts comprising: 1 bipolar transistor, 1 varactor, 3 inductors, 6 or more capacitors, 3 resistors and 16 microstrip line components. The reliability of each part will differ from each other: the mean time between failures MTBF (in hours) of each component are given as follows:-

1 bipolar transistor (MTBF=0.6×10^6 h)

1 varactor (MTBF=2.5×10^6 h)

3 inductors (MTBF=6.0×10^6 h)

6 or more capacitors (MTBF=4.2×10^6 h)

3 resistors (MTBF=6.4×10^6 h)

16 microstrip line components (MTBF=90×10^6 h)

The basic theory of reliability tells us that:

the failure rate is given as : $\lambda = 1 / \text{MTBF}$, (1)

and the reliability of each electronic component as a function of time can be written as:-

$$R(t) = \exp(-\lambda t). \qquad (2)$$

Applying this theory to the system of microwave components we can deduce the reliability of each component in table 1.

Component	MTBF (× million hours) per component	Failure Rate λ (per million hours) for each component	Reliability R(t) per component
Bipolar Transistor	0.6	1.67	$\exp(-1.67t \times 10^{-6})$
Varactor	2.5	0.4	$\exp(-0.4t \times 10^{-6})$
Inductor	6.0	0.167	$\exp(-0.167t \times 10^{-6})$
Capacitor	4.2	0.238	$\exp(-0.238t \times 10^{-6})$
Resistor	6.4	0.156	$\exp(-0.156t \times 10^{-6})$
microstrip line element	90	0.011	$\exp(-0.011t \times 10^{-6})$

Table 1. Table of reliability data for various components.

In the specialist area of microwave technology, each microwave component is normally critical on the overall function and/or performance of the system. In this case we will assume a failure of any one of the components will have a consequence on the whole system.

The reliability of the system i.e. the probability that the system of components (in series) will work: R_S is determined by equation 3: [9]

$$R_s = R_1 R_2 R_3 \ldots R_n = \prod_{i=1}^{n} R_i \tag{3}$$

where R_i is the reliability of the i'th part and n is the total number of parts.

Applying equation (3) to the data in table 1, the total reliability of the system can be determined as follows:-

$$R_S = \exp \{[- 1.67t - 0.4t - (3 \times 0.167t) - (6 \times 0.238t) - (3 \times 0.156t) - (16 \times 0.011t)] \times 10^{-6}\} \tag{4}$$

$$\therefore\ R_S = \exp (-4.643t \times 10^{-6}). \tag{5}$$

The MTBF for the whole system is: $10^6 \div 4.643 = 215{,}400$ hours = 24.6 years.

Figure 1 shows equation (5) represented as a reliability chart. The chart shows the reliability of the system decreases approximately linearly with hours of operation.

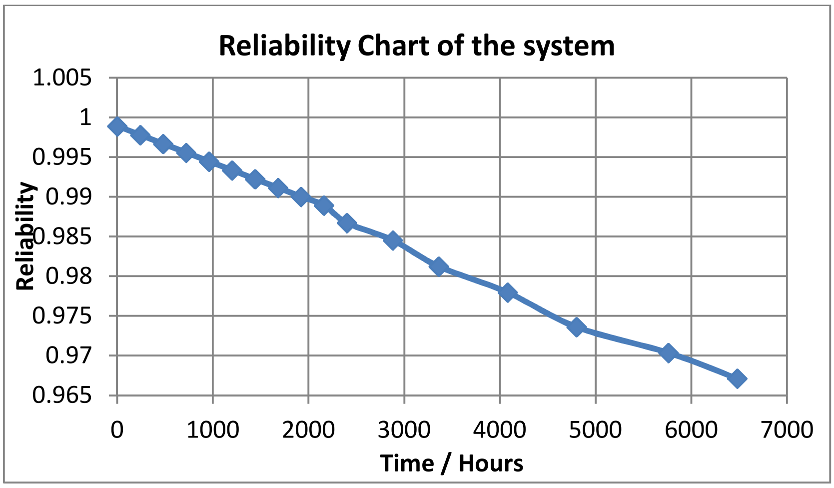

Fig 1 Reliability of a typical microwave frequency source

This voltage controlled oscillator is build primarily for military use and is therefore inherently reliable. The components in these devices are therefore robust and there are few components. For a system containing say a hundred parts, the MTBF would become reduced to around four years. Many space systems do contain thousands of individual components, all of which are required to stay reliable for, at least a decade. Such systems would be designed for reliability as their main criterion.

Note that the analytical method shown above uses basic theory to illustrate the reliability of microwave electronics. More precise and complex calculations of electronic components are carried out using the computational methods as discussed in section 2. This would include more considerations about the environmental conditions and stress factors that the components are subjected to and more complex types of configurations involving parallel and series calculations.

4 Conclusions

In this paper, many of the approaches to the design and manufacturing methods for reliability have been discussed. Aerospace and defence electronics are designed, primarily, for high performance and reliability. These components contain high quality materials and devices, robust eutectic type bonding and multiple connectors all contained within a hermetic type packaging. The burn-in procedures, quality control and testing are rigorous and there is very little tolerance for any contamination. Additional circuitry is also required to prevent fluctuations of the supply voltage. The overall cost of this technology, production and labour are many times that of a commercial product. Since reliability is the main criterion in defence, space and aerospace use, these components are the only viable option.

A cost reduction method, without compromising reliability, is to design component-in-package and to simplify the design so as to contain the least number of devices in the unit - ensuring that the performance or reliability of the system is not affected. The electronics can also be carefully designed so that there is room for tolerance of the parameter values as they vary with age.

A basic analytical prediction has been shown for a typical microwave frequency source. This prediction used reliability data for each of the on-board devices and deduced the total failure rate of the system and its reliability curve (versus time/hrs). The mean time between failures was calculated to be 24.6 years and the reliability of the frequency source decreased roughly linearly with time to 0.97 at 6000 hours. This analytical prediction was based on the correct assumption (in this example) that a failure of any one of the devices has a consequence on the whole system.

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