Radiation Considerations in the Design of Linear Microwave Transistor Amplifiers for Space Applications

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Abstract—**It has been shown recently that a number of different types of microwave transistors used in linear microwave amplifiers designed for space applications are radiation sensitive [3]. Since the transistor h_{FE} is the most radiation sensitive parameter, microwave performance of amplifiers intended for long space missions may degrade prematurely due to changes in transistor bias conditions. A description of the various factors affecting the overall radiation sensitivity of linear microwave amplifiers is given and is followed by experimental results of ground radiation testing on a *L*-band and a *S*-band preamplifier. Calculations based on the expected radiation dose levels in space show that neglecting the effects of radiation in amplifier design could lead to mission lives in the order of weeks instead of years. As a result of the experience gained with component and amplifier characterization, an approach to radiation hardening of microwave integrated-circuit transistor amplifiers is presented.**

I. Introduction

MICROWAVE amplifiers designed for use in satellite applications must not only satisfy electrical performance requirements corresponding to system design criteria but must also satisfy stringent size, weight, and power consumption requirements. Microwave integrated-circuit (MIC) techniques are widely used in satellite equipment because they are ideally suited to meet all these design criteria. Satellite equipment must function not only under environmental constraints due to mechanical and thermal stresses but also in a radiation environment. This is one extra constraint which has received a great deal of attention in the design of low-frequency equipment using radiation sensitive components such as CMOS integrated circuits [1]. The advent of communication satellites designed for long mission lives in the region of seven years in geosynchronous orbit and using some of the latest technology microwave transistors with unknown radiation sensitivity means that the situation should be assessed for higher frequency circuits. Microwave devices are assumed to be relatively insensitive to radiation effects, and nothing seems to have been published to the contrary. A recent review of the radiation sensitivity of microwave semiconductor devices by Chaffin [2] supports this assumption for displacement (i.e., bulk crystal) damage in medium- and high-power transistors and amplifiers irradiated with neutrons. These results, however, are not directly applicable to space equipment since space radiation consists mainly of lighter charged particles which can cause considerably greater damage due to ionization effects. It has been shown by one of the authors that, as expected, small signal microwave transistors are not sensitive to displacement damage from high energy electrons but can be extremely sensitive to ionizing radiation [3]. The degradation mechanism is different from that described by Chaffin for neutron damage, and a totally different approach is required, therefore, in the design of radiation resistant MIC amplifiers for space applications.

It is the purpose of this paper to show that the radiation environment must be considered together with the other environmental design criteria for space-borne microwave amplifiers. A general account of the problem is presented and is followed by two specific examples of different amplifier designs at *L* and *S* bands whose radiation sensitivity was investigated by component characterization and by irradiation of the amplifiers under simulated operating conditions. From the results of these experiments, design criteria for radiation hardening of microwave linear amplifiers are derived and presented in an overall approach to the problem. This approach should enable future satellite designs to benefit from the advantages of MIC technologies in the space environment without the limitations brought about by transistor degradation due to radiation effects.

II. Description of the Problem

The basic problem arises from the sensitivity of the h_{FE} of currently used microwave transistors to ionizing radiation. Typical degradations of the order of 50 percent may be expected in the lifetime of satellite equipment, and this compares with the normally expected change of 0.5-percent $°C^{-1}$ with temperature. An additional 10-percent degradation may be expected due to ageing. Linear MIC amplifiers are usually designed by means of the *S* parameters of the devices used, and these *S* parameters are functions of the bias current. If the bias current decreases as a result of h_{FE} degradation then the *S* parameters change with the result that the amplifier gain and stability margin decrease, and the noise figure increases. The dc-bias networks must therefore be designed to minimize such changes in bias current, but there is a practical limit

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with passive networks, and, in some cases, active networks must be used. In general, if these effects have not been considered at an early stage of hardware design, and the change in bias current cannot be held within acceptable limits, amplifier box shielding may have to be used with its consequent weight penalty. The latter approach is not always effective in certain designs and, without radical circuit redesign, the equipment may, even with added shielding, fail to maintain its performance for the life of the satellite. This section gives a detailed description of the problem which is presented in three basic parts: 1) the radiation environment, 2) the transistor radiation sensitivity, and 3) the effects on the circuit. It is necessary to make this division at the outset of the problem in order to identify the major design factors which interact in the overall satellite system.

A. Radiation Environment

Most modern communication satellites operate in the geosynchronous orbit where the major contribution to the radiation environment comes from high energy electrons. These particles impinge on a spacecraft from all directions, but various parts of the structure and equipment boxes act as shields for the electronic components. It is the radiation environment inside the equipment boxes and, in fact, that which is at the active transistor chip level which is of the most practical interest. In the case of components which are sensitive to the ionizing properties of the radiation only, the most useful way of presenting this environment is by means of a dose-depth curve.

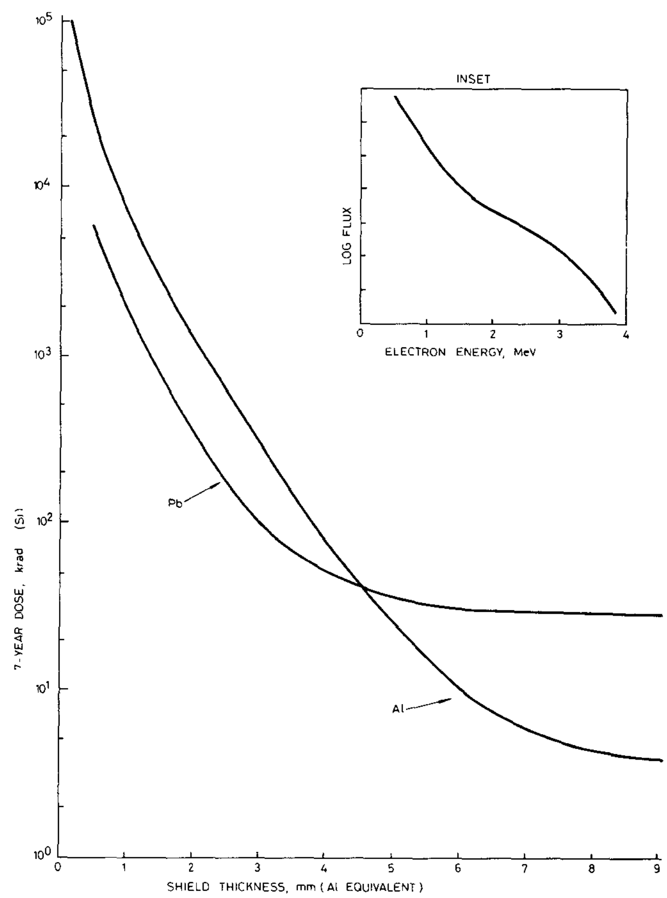


Fig. 1. Dose-depth curves for Al and Pb shields in the geosynchronous orbit after Holmes–Siedle and Freeman [1]. The inset shows a schematic of a typical electron spectrum in this orbit.

Fig. 1 shows such a curve which has been recently presented by Holmes–Siedle and Freeman in connection with a similar design problem in the application of CMOS devices in space [1]. The curve shows the ionizing radiation for a piece of silicon which is surrounded by an equal thickness of aluminium. Aluminium is used extensively for satellite structures and equipment boxes, and this, therefore, is the most useful radiation environment design curve. The inset in Fig. 1 shows schematically the energy spectrum of electrons impinging on the shield since these particles make the greatest contribution to the dose. For small shielding thicknesses only the low-energy electrons are stopped by the aluminium, and when the remaining spectrum is converted into its ionizing power in rad (Si)[1], this results in a relatively high-dose figure. The dose-depth curve flattens out at larger shielding thicknesses, and this is due to the contribution of dose from penetrating bremsstrahlung X-rays which are created by the stopping mechanism for the lower energy electrons. Fig. 1 shows the total dose-depth curve for aluminium taking electrons, solar protons, and bremsstrahlung X-rays into account [1]. The radiation environment in any part of a satellite equipment may, in principle, be calculated using such a curve. It is important to note two major features. First, the seven-year cumulative dose for exposed boxes with aluminium lids $\leqslant 1$ mm thick will be in the order of Mrads (Si), and, secondly, it is impractical to shield to <4 krads (Si) due to bremsstrahlung X-rays. Heavy element shields such as lead which are sometimes used as added shielding can give a better weight for weight dose reduction as seen from the dose-depth curve for equivalent weights of lead in Fig. 1. This curve also indicates a very much higher bremsstrahlung contribution of ~ 30 krads (Si) from the lead shield, and this limits its applicability. Many MIC amplifier boxes are machined to reduce weight and are also often situated close to the outer frame of the spacecraft. In practice the radiation environment in these cases is expected to be of the order of Mrads (Si) over seven years and any transistor which is sensitive to ionizing radiation at these dose levels must be examined in more detail to determine whether or not the environment can cause equipment performance degradation. Transistor characterization is very important, and the next part of this section considers this subject in more detail.

[1]A rad is the absorbed dose of any ionizing radiation which is accompanied by the liberation of 100 ergs of energy per g of absorbing material.

B. Transistor Radiation Sensitivity

It has been shown recently that several types of small signal transistors which are widely used in space equipment are sensitive to ionizing radiation [3]. These devices were irradiated with high-energy (1-MeV) electrons in the first instance to determine whether the major degradation mechanism was displacement or ionization damage. Once it was determined that ionization damage caused the degradation, X-rays from a tungsten target bremsstrahlung source were used as the irradiation source since it was more practical to bias individual components or equipment boxes with this source. Both irradiation sources result in equivalent electrical effects, and, although neither completely reproduces the complex space radiation environment, this is not a serious limitation since it is the cumulative ionizing radiation dose, regardless of origin, which determines transistor degradation. It is relevant to note here that the only recent experiment designed to measure radiation sensitive semiconductor devices in a space radiation environment with different shielding conditions has proved the validity of ground irradiation simulation using an ionizing radiation source [4]. The aforementioned experiment is still under way using CMOS integrated circuits where the basic physical degradation mechanism is similar to that for microwave transistors [3]. It is expected, therefore, that the degradation of microwave transistors in a space environment may also be simulated by ground testing using standard ionizing radiation sources.

A detailed study of three different types of transistors from the same manufacturer has shown that their inherent radiation sensitivity is the same. The results of h_{FE} sensitivity, therefore, can be summarized in one curve for each collector current as shown in Fig. 2. These curves show the sensitivity of the normalized dc current gain $H \equiv h_{FE}/h_{FE0}$ as a function of h_{FE0} for one irradiated dose level (5.10^2 krads (Si)). The results represent about fifty devices comprising the three different device types (designated A, B, and C) which have been irradiated with X-rays under bias. Since the inherent sensitivity of the normalized dc current gain $H \equiv h_{FE}/h_{FE0}$ is the same, the device types are only differentiated by their range of h_{FE0} values. The actual range of h_{FE0} values is 40–180, and the curves have been extrapolated beyond these values using the analytical function for H derived by one of the authors [3].

It is seen from Fig. 2 that device h_{FE} values degrade significantly in the dose[2] range which is expected on board a satellite. This degradation depends more on the preirradiation value h_{FE0} than on the transistor type or collector current. Since h_{FE} degradation saturates at doses greater than 5.10^2 krads (Si), maximum degradation effects for these three types of transistors may be predicted using Fig. 2, or, if required, more detailed degradation behavior may be calculated from the equations developed in [3]. It appears from preliminary experiments that the radiation sensitivity of microwave transistors could vary as much as that found in CMOS integrated circuits, i.e., from krads to Mrads [1], [3].

[2]All doses are referred to the silicon chip position.

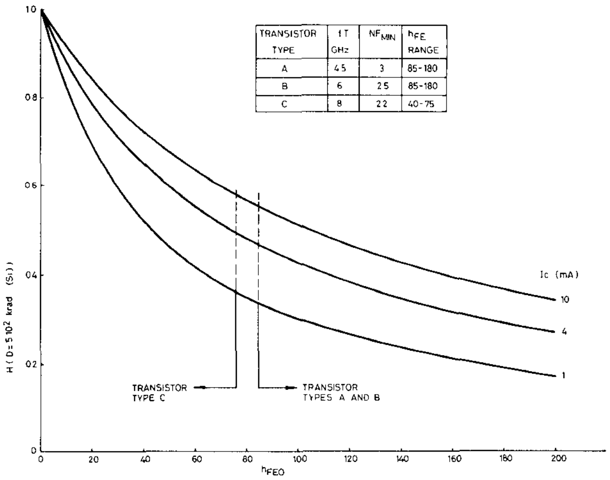


Fig. 2. Dependence of normalized h_{FE}, H on starting value, h_{FE0} and collector current, I_C for three different transistor types. The basic electrical characteristics of the transistors are shown in the inset.

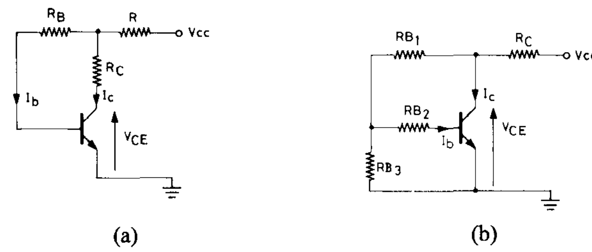


Fig. 3. Commonly used passive bias networks. (a) Voltage feedback. (b) Voltage feedback plus constant base current source.

Since the transistor types shown in Fig. 2 are the most widely used in small-signal MIC amplifiers for satellite applications, the rest of the paper will concentrate on the effect of their h_{FE} degradation. Characterization methods and design criteria which emerge from this work nonetheless are applicable to other similar transistors and amplifier designs. The next part of this section concentrates on the effect of h_{FE} changes on the device performance.

C. Effects on the Circuit

1) Passive Bias Circuit Considerations: If passive bias circuits are used in the amplifier design, then some feedback must be employed to reduce the sensitivity of bias current I_C to changes in h_{FE}. A commonly used bias network is that employing voltage feedback shown in Fig. 3(a) [5]. If the effects of reverse leakage current I_{CB0} are neglected, the current sensitivity to changes in h_{FE} is given by

$$\frac{\Delta I_C}{I_C} = \left(\frac{R_B}{R_B + h_{FE} R} \right) \frac{\Delta h_{FE}}{h_{FE}}. \qquad (1)$$

The resistor R_C can be included to set the bias value of V_{CE} without affecting the current sensitivity. For numerical values typical of low noise applications, viz., $h_{FE}=$ 50–200, $I_C = 3$–5 mA, $V_{CE} = 8$ V, $V_{CC} = 15$ V, (1) becomes

$$\frac{\Delta I_C}{I_C} \sim 0.4 \frac{\Delta h_{FE}}{h_{FE}}.$$

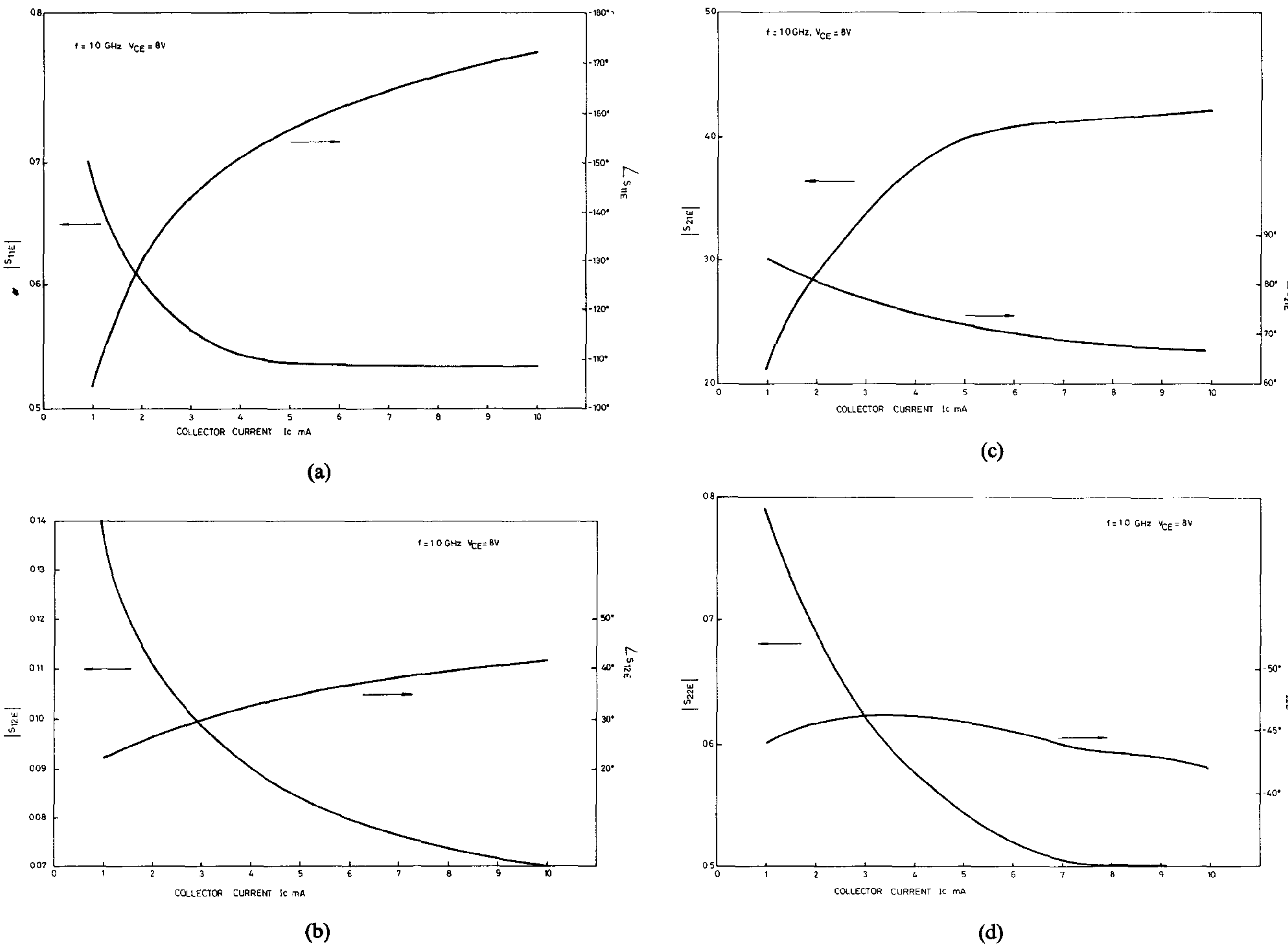


Fig. 4. Typical S-parameter dependence on collector current for transistor types A, B, and C. (a) S_{11}, (b) S_{12}, (c) S_{21}, (d) S_{22} for a type A transistor operating at 1 GHz.

This shows that for a -50-percent change in h_{FE} the corresponding drop in bias current $I_C = 20$ percent. From a knowledge of S parameters and noise figure variation with bias current plus a knowledge of the network topology, the amplifier performance can be evaluated. A set of typical S parameters/bias current characteristics are shown in Figs. 4(a)–(d) together with a typical noise figure characteristic in Fig. 5. The transistor itself is unlikely to suffer noise figure degradation due to h_{FE} changes as the h_{FE} would have to degrade to a very low value before such an effect would occur. A low-noise amplifier, however, would suffer in general a noise figure increase since the decreasing bias current of the transistor would move the dc operating point to a position of a higher noise figure (see Fig. 5). In addition, the input-circuit topology would no longer present the transistor with the optimum source impedance at this new bias level. For a characteristic decreasing bias current due to h_{FE} degradation, $|S_{21}|$ decreases, $|S_{12}|$ increases, usually at a greater rate, and this results in an increase in the product $|S_{21}| \cdot |S_{12}|$. In general, this causes the stability factor K to fall with consequent reduction in amplifier stability margins. A second bias network both employing voltage feedback and providing a constant base current source is shown in Fig. 3(b) [5]. The corresponding current sensitivity to changes in h_{FE} is given by

$$\frac{\Delta I_C}{I_C} = \left(\frac{R_{B2}(R_{B1} + R_{B3} + R_C) + R_{B3}(R_C + R_{B1})}{R_{B2}(R_{B1} + R_{B3} + R_C) + R_{B3}(R_C(h_{FE} + 1) + R_{B1})} \right) \cdot \frac{\Delta h_{FE}}{h_{FE}}$$

and for the same bias conditions considered above

$$\frac{\Delta I_C}{I_C} \sim 0.4 \frac{\Delta h_{FE}}{h_{FE}}.$$

Although this bias current is similar to the pure voltage feedback case when considering h_{FE} variations only, it is considerably better for stabilizing the amplifier bias current over a temperature range when the variations in V_{BE} and I_{CB0} are included and, therefore, is preferred.

2) Active Bias Circuit Considerations: A common active bias circuit used for biasing linear microwave transistors is shown in Fig. 6 [6]. Various derivatives of this basic circuit

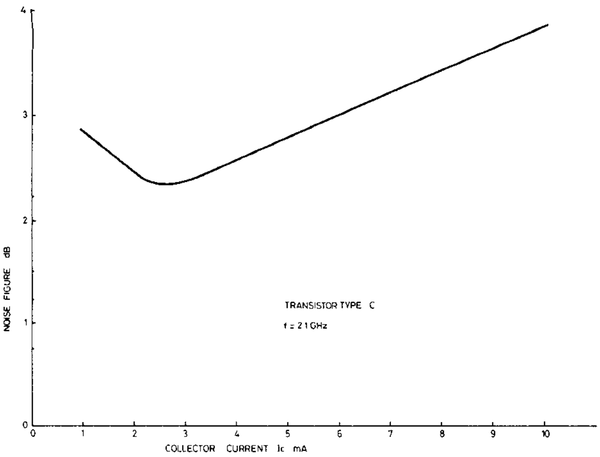


Fig. 5. Typical noise figure dependence on collector current for transistor type C operating at 2.1 GHz.

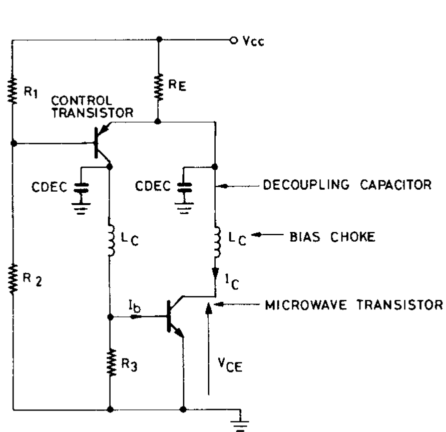


Fig. 6. Typical active bias network.

incorporating diodes to improve the temperature performance are also used. The advantage of the active bias network is that the bias collector current I_C through the microwave transistor is controlled by the emitter resistance R_E and the supply voltage V_{CC} of the constant current source defined by the p-n-p control transistor. The bias current is therefore virtually independent of the h_{FE} of the microwave and control device. The current sensitivity of this circuit configuration to changes in h_{FE} is given by

$$\frac{\Delta I_C}{I_C} = \frac{1}{1+h_{FE}} \frac{\Delta h_{FE}}{h_{FE}}.$$

If h_{FE} reduces by X percent and $h_{FE}=50$, for example,

$$\frac{\Delta I_C}{I_C} < 0.02\, X \text{ percent}$$

and change in bias current is minimal. This is obviously the preferred bias configuration for it eliminates essentially the change in bias current due to the h_{FE} degradation. The disadvantage of this circuit configuration for space application is its greater complexity plus the use of an additional p-n-p transistor. This greater complexity must be traded off against the option of the simpler passive bias networks plus increased box shielding with corresponding weight penalty. This is discussed further in Section IV.

III. Irradiation Experiments on Amplifiers

This section presents the results of performance degradation measurements on amplifiers due to ionizing radiation. Experiments on two amplifier modules are presented in some detail since they illustrate a number of different problems which require different solutions. The common factor was the use of radiation sensitive transistors in each design. Both experiments were conducted in a manner similar to that carried out for X-ray irradiation of transistors under bias, and the dose rates used were 10–100 rad (Si) s^{-1}. Preirradiation microwave performance measurements were carried out in each case, and the sensitivity of the RF parameters to dc supply current changes were also determined to give an indication of the changes which may be expected due to irradiation. The results for the L- and S-band low-noise preamplifiers are presented below.

A. L-Band Preamplifier (Centered at 1.05 GHz)

A schematic diagram of this preamp is shown in Fig. 7 along with the dc bias circuit for each transistor. The amplifier consisted of two-type A and two-type B transistors in cascade. It should be noted that this amplifier is of the type which has no feedback resistor in the bias circuits (except for R_9 which has a small desensitizing effect on the fourth stage), and h_{FE} changes are expected to have the maximum effect on S parameters and the overall microwave performance. For this bias configuration, the current sensitivity is given by

$$\frac{\Delta I_C}{I_C} = \frac{\Delta h_{FE}}{h_{FE}}.$$

Thus for X-percent change in h_{FE}, there is a corresponding X-percent change in bias current. Fig. 8(a) shows the amplifier gain as a function of radiation dose alongside the average measured h_{FE} behavior for each of the two types of transistors used in the preamplifier at their corresponding bias levels.

Results for similar devices, biassed at 3.5 and 10 mA and characterized separately from the amplifier, are also shown in Fig. 8(a) at the 50 krads (Si) dose level. The h_{FE} degradations agree within 5 percent. The gain change prior to irradiation due to uniform supply current only is also shown in Fig. 8(b), and it is apparent that the radiation-induced changes are considerably greater than those expected from simple uniform current changes only. The reason for this is the differential degradation of each device bias current with irradiation dose, i.e., the low bias current devices (the two-type A devices biassed at 3.5 mA) will degrade more rapidly than the higher current devices. The corresponding change in S parameters (particularly on the first two transistors) when interacting with the external circuit produces a greater gain rolloff than that

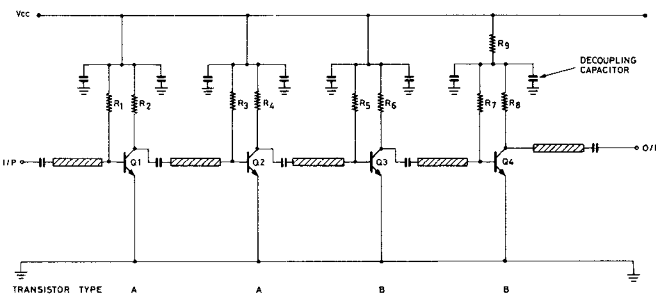
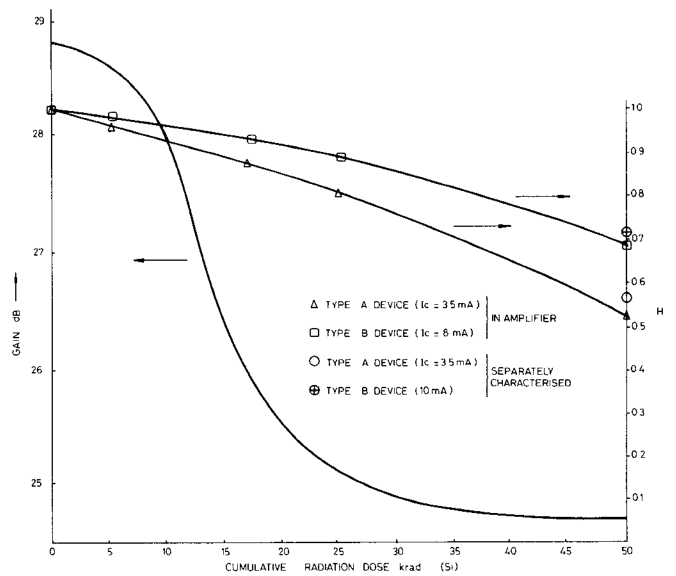
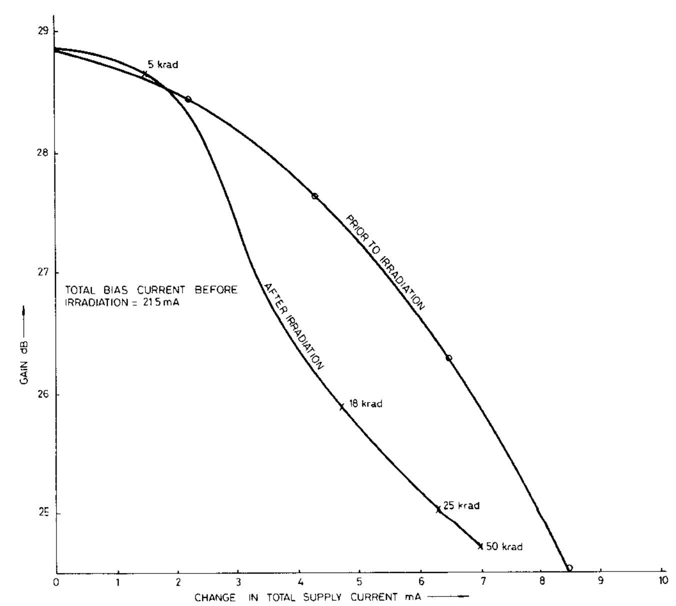


Fig. 7. L-band preamplifier schematic.



(a)



(b)

Fig. 8. The effects of radiation on L-band amplifier performance. (a) Amplifier gain and corresponding transistor h_{FE} degradation. (b) Amplifier gain before and after irradiation as a function of change in total supply current.

associated with the uniform current change, where each device bias current reduces by approximately the same percentage as the supply volts are decreased. Table I

TABLE I
PERFORMANCE DEGRADATION FOR EACH OF THE TRANSISTORS USED IN THE L-BAND PREAMPLIFIER

Transistor	Q1	Q2	Q3	Q4	
Transistor type	A	A	B	B	
Initial bias current (mA)	3.5	3.5	8	6.5	
Final bias current (mA) after 50 krad(Si) exposure	1.84	2.02	5.5	5.1	
% change in h_{FE}	47	43	31	27	
Change in $\|S_{21}\|^2$ dB	−2.2	−1.8	−0.25	−0.25	$\Sigma\|S_{21}\|^2 = -4.5$ dB

shows the change in bias current with the corresponding change in h_{FE} for each of the stages of the preamplifier after 50-krads (Si) irradiation exposure. For the first two stages using type A devices, the percentage h_{FE} degradation, i.e., 47 and 43 percent, is similar to the degradation shown for the type A device at 50 krads (Si) shown in Fig. 8(a). The third and fourth stages using type B devices degrade by 31 and 27 percent, respectively, and this compares reasonably well with the high current h_{FE} degradation also shown in Fig. 8(a).

The change in forward gain for each of the devices $|S_{21}|^2$ is also shown in Table I. These values are estimated from the typical S parameter versus bias current characteristics of Figs. 4(a)–(d). From the table it can be seen that the preamplifier gain degradation after exposure to 50 krads (Si) of irradiation is -4.5 dB based upon $|S_{21}|$ degradation only. This compares well with the -4.1-dB degradation measured in practice. The theoretical gain degradation is obviously a first approximation, since all other S parameters change by about 10 percent and these changes will interact with the external circuitry to produce further changes in gain. It is also interesting to note that after the steep gain drop the gain curve flattens out due to the h_{FE} saturation effect at higher dose levels [3]. Since the gain margin of this amplifier is specified as ± 2 dB, the failure dose is approximately 15 krads (Si).

The time to failure for this amplifier may be calculated, knowing its position in the satellite, by determining the dose at the transistor chips using the dose-depth curve of Fig. 1. This calculation is based on the assumption that the h_{FE} degradation is permanent and depends only on cumulative radiation dose. Thermal annealing experiments on these types of transistors irradiated with X-rays and 1-MeV electrons support this assumption [3]. In the particular application intended for amplifiers of this type, some were suspended from the spacecraft structure with the lid of the MIC box facing outward into space with initially no shielding while others faced inwards and were shielded by the spacecraft. It should be noted that this satellite design uses a paddle solar-cell panel design which does not give the natural shielding afforded by wrap-around solar-cell panel designs [1].

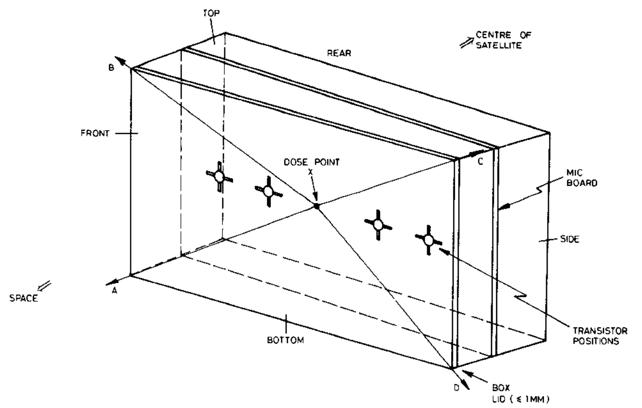


Fig. 9. Schematic of L-band amplifier box showing the position of the transistors, dose point X, and its geometrical relationship to the environment.

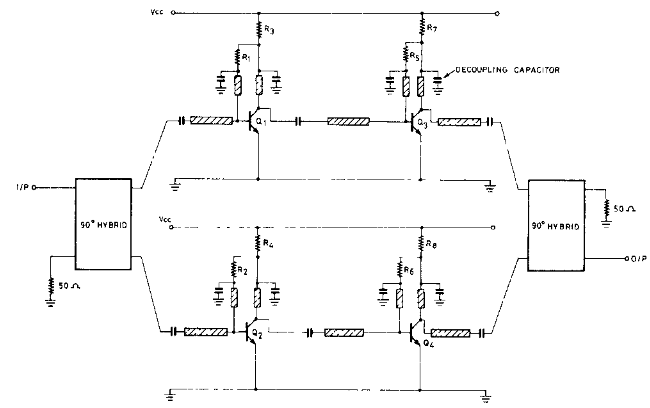


Fig. 10. S-band preamplifier schematic.

TABLE II
6-SECTOR ANALYSIS OF 7-YEAR DOSE AT POINT X IN FIG. 9

SECTOR	SHIELDING (mm Al equivalent)				Nominal dose (Fig 1) krad(Si)	Geometrical dose reduction factor	Actual dose krad(Si)
	Transistor package	Wall of box	Spacecraft	Total			
Rear	0.75	3	6	9.75	4	0.38	1.5
Side	0.75	3	0.4	4.2	60	~0.01	0.6
Side	0.75	3	0.4	4.2	60	~0.01	0.6
Top	0.75	3	0.4	4.2	60	0.10	6
Bottom	0.75	3	0.4	4.2	60	0.10	6
Front	0.75	1	0	1.75	1.7 10³	0.38	646
						Approx Total	650

Fig. 9 shows how the radiation dose was calculated for the worst case amplifiers facing outwards. The dose at point X in the center of the box is calculated by dividing the box into six sectors. The front sector, defined by the solid angle subtended at X by the MIC box lid $ABCD$, serves as an example of this calculation. This sector subtends approximately 40 percent of 4π, and thus the seven-year radiation dose is 40 percent of the value given by the dose-depth curve of Fig. 1 for the total aluminium equivalent shield thickness due to the box lid and transistor package. Table II shows how this hand analysis is carried out for all six sectors, taking into account the shielding of the transistor package. Clearly the front sector accounts for most of the total dose of 650 krads (Si) in seven years. From the known failure dose a survival time of less than three months is predicted in space. Adding lead shielding to this amplifier design does not solve the problem since the failure dose level of 15 krads (Si) is still less than the 30-krads (Si) shield limit expected for lead from Fig. 1.

Although the above calculated sector analysis approach is simplified, it is justified in the simple case of a thin walled box looking straight into space. More complex geometrical configurations may require sector analysis using computer-aided methods [4]. Even the dose level computed by simple hand methods is only as accurate as the dose-depth curve which is itself derived from a prediction of the space environment. Inaccuracies in environment models are likely to be larger than those due to computational methods [4], and we estimate the failure dose to lie within the range 10 krads (Si)–40 krads (Si). Sector analysis of the above type cannot be used to give more than an indication of whether or not the survival time in space is likely to be acceptable or not. Accurate predictions cannot be made over seven-year periods for orbits, such as the geosynchronous orbit, where long term space radiation environment measurements have not yet been made. If circuit redesign or component reselection is not possible in amplifiers such as that described above, then the only possibility of achieving the seven-year mission life for this type of equipment is to use a thicker aluminium box with a minimum thickness of 6 mm all round. Local component shielding would not be an acceptable solution in this type of amplifier since the addition of any metal internal to the box in the vicinity of the transistors would drastically affect their microwave performance (capacitive loading, etc.). This amplifier is a worst case design example in which radiation sensitive transistors are used in a bias circuit which is totally h_{FE} sensitive and where the whole equipment is in an exposed position in the satellite and receives the maximum radiation dose. The penalty is extra weight and no positive assurance of meeting the required operating mission life.

B. S-Band Preamplifier (Centered at 2.1 GHz)

This amplifier was designed for use in a completely different satellite from that of the previous amplifier. Four transistors of type C were used in a balanced configuration in a switched parallel redundancy circuit as shown in Fig. 10. The bias circuits were somewhat less sensitive to h_{FE} changes than those of the L-band amplifier being of the type shown in Fig. 3(a) and, for the bias components used, the current sensitivity is

$$\frac{\Delta I_C}{I_C} \sim 0.4 \frac{\Delta h_{FE}}{h_{FE}}.$$

One half of the amplifier was irradiated, and the other half was shielded and used as a control reference. The gain and noise figure as a function of cumulative dose is shown in Fig. 11. It can be seen that a very rapid decrease in gain and increase in noise figure result at moderately

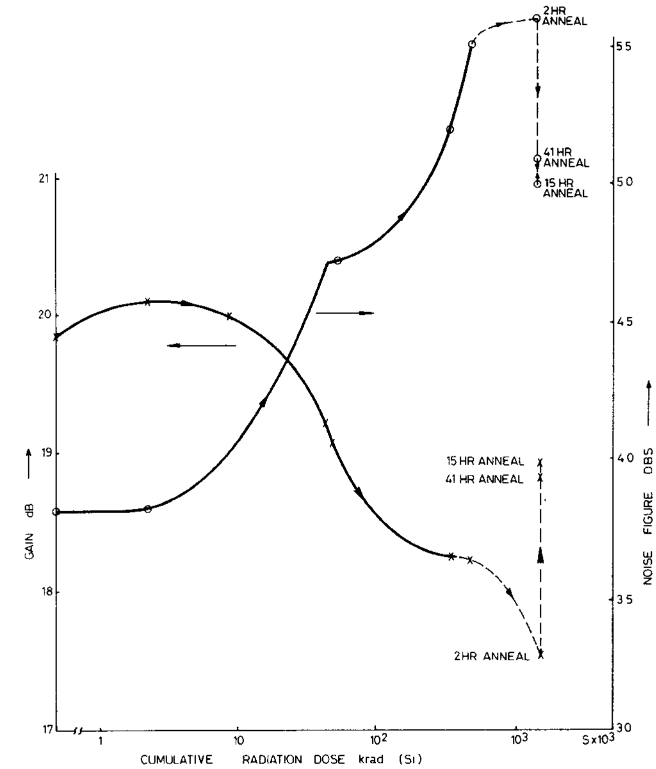


Fig. 11. The effects of radiation on S-band amplifier performance also showing postirradiation annealing.

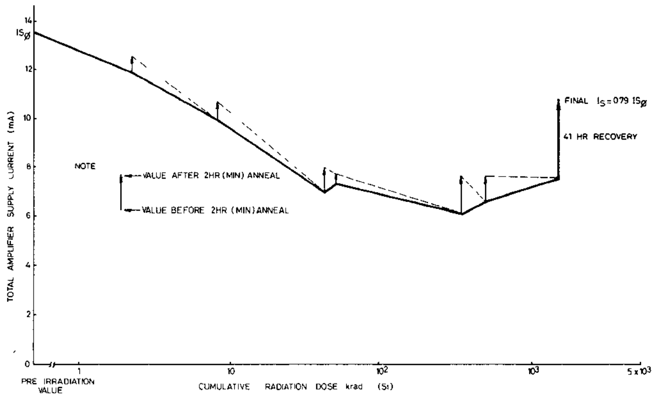


Fig. 12. Radiation-induced degradation and annealing effects of the total supply current for the S-band preamplifier.

low doses. There is a somewhat anomalous behavior at the 1.5-Mrads (Si) dose level whereby the gain recovers and the noise figure falls. The anomalous annealing (recovery) mechanism was noted from the beginning of the irradiation procedure when the supply current and device h_{FE} degradation were faster than normal. Fig. 12 shows the total supply current as a function of irradiation dose, and it can be seen that, in addition to a fast initial degradation, significant annealing occurred during the two-hour relaxation periods with the effect being more pronounced at higher dose levels. In fact for doses beyond 1.5 Mrads (Si) the amplifier started to anneal under irradiation. Fig. 13 shows the measured h_{FE} degradation of one type C transistor along with the measured degradation of the devices in the amplifier after annealing. This anoma-

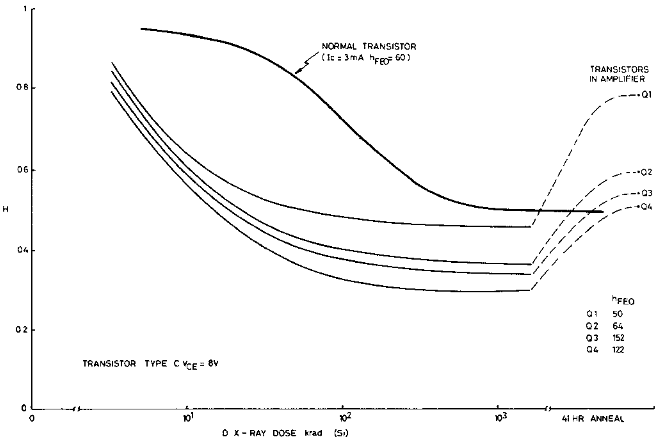


Fig. 13. Radiation-induced degradation and annealing effects on the normalized h_{FE} of the four transistors used in the S-band preamplifier. A typical curve for a normal transistor of the same type is shown for comparison.

TABLE III
PERFORMANCE DEGRADATION FOR EACH OF THE TRANSISTORS USED IN THE S-BAND PREAMPLIFIER

Transistor	Q1	Q2	Q3	Q4	
Initial bias current (mA)	2 9	3 95	2 83	4 05	
Final bias current (mA) after 1 5 Mrad (Si) exposure	1 95	2 84	2 05	3 6	
% change in h_{FE}	47	43	40	21	
Change in $\|S_{21}\|$ dB	−1 1	−1 0	−1 0	−0 34	Δ gain − 1 7 dB*

Assuming in balanced amplifier configuration Δ gain $\sim \frac{1}{2}[\sum_{1}^{4} |S_{21}| \text{dB}]$.

lous degradation appears to coexist with the normal h_{FE} degradation to which the transistors return after a sufficiently long anneal time. Devices from exactly the same lot as that used in construction of this amplifier were not available for detailed investigation of the anomalous behavior. No other transistors of this type showed the same effect [3].

The theoretical change in forward gain for each of the devices and for the complete amplifier is shown in Table III. These values are determined from the S-parameter measured data of a single device. From the table it can be seen that the predicted amplifier gain degradation is approximately 1.7 dB after 1.5-Mrads (Si) irradiation exposure compared with the measured value of 1 dB. As before, this gain degradation is based upon $|S_{21}|$ changes only. A sector analysis of this amplifier has been carried out in the way described for the L-band equipment. The S-band amplifier has a much thinner lid (0.3-mm Al) which faces out into space but has the advantage of some protection due to the solar cell panel which in this design encloses the whole satellite. Sector analysis results in a predicted dose of approximately 4 krads (Si) per week. The survival times predicted on this basis for different

TABLE IV
SURVIVAL TIME PREDICTIONS FOR DIFFERENT FAILURE CRITERIA

Parameter	Failure criterion	Dose required at silicon chip krads (Si)	Predicted survival time weeks
Noise Figure	4.5 dB	20	5
Gain	−0.5 dB −1.0 dB	23 43	6 10

performance degradation criteria are shown in Table IV. Despite the use of a less sensitive dc bias circuit, this amplifier clearly cannot be considered for reliable long term operation in its present form since the survival times are in the region of 5–10 weeks. If greater margins are allowed for the failure criteria (e.g., gain degradation of >2 dB) the radiation dose would be in the region where anomalous annealing may begin.

IV. Approach to Radiation Protection Design

It is clear from the previous sections that radiation protection is not necessarily a simple matter of adding shielding. A total design approach in fact is required which includes appropriate device and circuit characterization at as early a stage in the design as possible. Fig. 14 shows a simplified flow diagram which offers an approach based on the results of the previous section to ensure that operational times are not reduced to unacceptable levels due to the radiation environment. A few salient points relating to this flow chart are discussed in more detail in the following paragraphs.

A. Component Characterization and Selection

It has been shown in Section II-A that, even where a device may be inherently sensitive, as with all the transistor types *A*, *B*, and *C*, the transistor with the lowest starting value of h_{FE} has the lowest radiation sensitivity. Where possible, devices from the same lot should be characterized for radiation sensitivity, and, if the h_{FE} change is less than 10 percent at 1 Mrad (Si), it may be considered as insensitive. All room temperature annealing effects must be regarded as anomalous and may even indicate a reliability problem which may show up on life test or high temperature reverse bias which comprise a space component screening program. Although the device types presented here have shown a relatively sensitive *S*-parameter–collector-current relationship, this may not always be the case for applications where, for instance, low-noise figures are unimportant and higher collector currents are possible. Choice of bias points in the flat part of the curves as shown in Fig. 4 will desensitize the device to h_{FE} changes.

B. Circuit Analysis

From the h_{FE} radiation sensitivity data in conjunction with the *S* parameter/bias and, in some applications, noise figure/current data for the devices, the effect can be determined on the overall amplifier performance (i.e., gain and noise figure degradation plus stability margins). These computations assume a knowledge of the bias network configuration in order to estimate the change in bias current with change in h_{FE}.

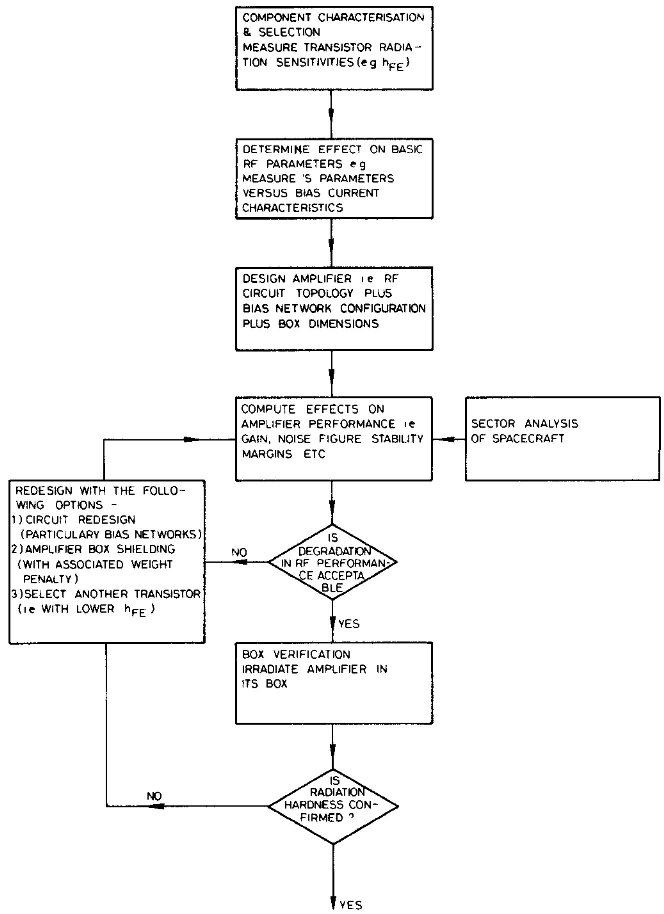


Fig. 14. Flow diagram illustrating a possible approach for the design of microwave linear amplifiers for space applications.

C. Equipment Shielding

A sector analysis of the whole spacecraft should be available at an early stage of design. Equipment which has been determined to be sensitive may benefit from a resiting in the satellite structure. For example, turning the *L*-band amplifiers discussed in Section II-B so that they faced inwards toward the satellite center would have helped to extend the predicted survival time considerably. MIC equipment boxes may benefit from the natural shielding afforded by siting them behind waveguide equipment. Add-on shielding is the least satisfactory design approach since it may necessitate a complete reanalysis of the dose levels within the rest of the satellite. It is usually a last minute step which may be impossible due to equipment inaccessibility.

D. Optimized Approach

The aforementioned procedures which have been dealt with separately may be optimized if they are carried out in the sequence shown in Fig. 14. It should be clear, however, that if radiation protection ultimately cannot be assured within the design limits of the satellite, the options which are left necessitate a reiteration of the whole or part of the procedure. It should also be emphasized that the survival time prediction techniques based on equipment irradiation and sector analysis are not precise. If the survival time is of the same magnitude as the mission life, then redesign is necessary for radiation protection assurance. At the present time an estimated survival time of 2–3 times longer than the design mission life is preferred. It is also possible that the use of a less radiation sensitive transistor with a poorer microwave performance is a preferable solution to the use of high-performance devices which may degrade more quickly.

V. Conclusions

It has been shown that if the ionizing radiation environment is not taken into consideration during the design of MIC linear transistor amplifiers for space applications, the survival time of the equipment may be considerably less than the mission life. One means of overcoming this problem is the use of dedicated active bias networks for each stage of the amplifier. This approach requires more components and increased box dimensions (with a weight penalty) and may lead to a reduction in reliability. Most bias networks presently used are passive, and, if this design approach is used in future applications, a more optimum procedure similar to that outlined in Fig. 14 is required in order to ensure radiation hardness. Although the practical examples given refer to the geosynchronous orbit, the same design approach is applicable to other missions where the appropriate radiation environment can be estimated.

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Sensitivity Analysis of Coupled Microstrip Directional Couplers

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***Abstract*—Sensitivities of the parameters (coupling, bandwidth, and impedance) of a coupled-line directional coupler with respect to even- and odd-mode impedances have been evaluated. These are used to determine the accuracy required from the closed-form expressions for even- and odd-mode impedances of microstriplines. Closed-form expressions satisfactory for a coupling coefficient greater than 0.3 are proposed and used for evaluating the effect of dimensional tolerances on the performance of microstrip directional couplers. This effect is significant when compared with effects of unequal phase velocities and dispersion.**

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I. Introduction

Coupled microstriplines are used extensively in microwave and millimeter-wave circuits [1] to design directional couplers, filters, impedance transformers, and delay lines. There have been many calculations available for even- and odd-mode impedances of coupled lines [2]–[7]. The earliest and presumably the most widely used analysis (neglecting dispersion) is by Bryant and Weiss [2]. This method requires extensive computations [7], and the results have been tabulated for some specific values of the dielectric constant ($\epsilon_r = 1, 6, 9, 12, 16, 30, 80$) [7], [8]. Schwarzmann [3] has proposed closed-form relations for

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