Lecture Notes in Electrical Engineering 963

Chander Prakash
V. Sambasiva Rao
D. V. A. Raghava Murthy *Editors*

Smart Small Satellites: Design, Modelling and Development

Proceedings of the International Conference on Small Satellites, ICSS 2022

Springer

Lecture Notes in Electrical Engineering

Volume 963

The book series *Lecture Notes in Electrical Engineering* (LNEE) publishes the latest developments in Electrical Engineering—quickly, informally and in high quality. While original research reported in proceedings and monographs has traditionally formed the core of LNEE, we also encourage authors to submit books devoted to supporting student education and professional training in the various fields and applications areas of electrical engineering. The series cover classical and emerging topics concerning:

- Communication Engineering, Information Theory and Networks
- Electronics Engineering and Microelectronics
- Signal, Image and Speech Processing
- Wireless and Mobile Communication
- Circuits and Systems
- Energy Systems, Power Electronics and Electrical Machines
- Electro-optical Engineering
- Instrumentation Engineering
- Avionics Engineering
- Control Systems
- Internet-of-Things and Cybersecurity
- Biomedical Devices, MEMS and NEMS

For general information about this book series, comments or suggestions, please contact leontina.dicecco@springer.com.

To submit a proposal or request further information, please contact the Publishing Editor in your country:

China

Jasmine Dou, Editor (jasmine.dou@springer.com)

India, Japan, Rest of Asia

Swati Meherishi, Editorial Director (Swati.Meherishi@springer.com)

Southeast Asia, Australia, New Zealand

Ramesh Nath Premnath, Editor (ramesh.premnath@springernature.com)

USA, Canada

Michael Luby, Senior Editor (michael.luby@springer.com)

All other Countries

Leontina Di Cecco, Senior Editor (leontina.dicecco@springer.com)

**** This series is indexed by EI Compendex and Scopus databases. ****

Chander Prakash · V. Sambasiva Rao ·
D. V. A. Raghava Murthy
Editors

Smart Small Satellites: Design, Modelling and Development

Proceedings of the International Conference on Small Satellites, ICSS 2022

Springer

Editors
Chander Prakash
Division of Research and Development
School of Mechanical Engineering
Lovely Professional University
Phagwara, Punjab, India

D. V. A. Raghava Murthy
Centre for Space Research
Lovely Professional University
Phagwara, Punjab, India

V. Sambasiva Rao
Crucible of Research and Innovation
Centre for Research in Space Science
and Technology
PES University
Bengaluru, Karnataka, India

ISSN 1876-1100 ISSN 1876-1119 (electronic)
Lecture Notes in Electrical Engineering
ISBN 978-981-19-7197-6 ISBN 978-981-19-7198-3 (eBook)
https://doi.org/10.1007/978-981-19-7198-3

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Preface

Smart Small Satellites: Design, Modelling and Development presents select proceedings of International Conference on Small Satellites and Its Applications (ICSS-2022) and aims to a comprehensive and broad-spectrum picture of the state-of-the-art research, development and commercial prospective of various discoveries conducted in the real-world Smart Small Satellites, applications and their services. The thematic issue also covers the involvement of various advanced software-driven techniques that need to be employed for deploying efficient power management system, application-based optimum payload designs, telemetry and telecommand, advanced navigation and RF systems, flight and ground software, structure, mechanism and materials, spacecraft autonomy, quality, testing and reliability for designing the small satellites through advanced computational procedures for a variety of applications. Here, the authors provide graduate, postgraduate, doctorate students, faculty and scientists with an in-depth account of the evolutionary behaviour of Smart Satellites and their Engineering for educational, societal and industrial applications. The issue also covers application of advanced and functional material for development of small satellites and payloads. The book can be a valuable reference for beginners, researchers and professionals interested in design, modelling and development of smart small satellites through advanced computing technologies.

Phagwara, India — Chander Prakash
Bengaluru, India — V. Sambasiva Rao
Phagwara, India — D. V. A. Raghava Murthy

Contents

About the Editors

Prof. Chander Prakash is working as a Professor and Dean (Associate), Division of Research and Development, Lovely Professional University, Punjab, India. He is Adjunct Professor (Honorary position) at Institute for Computational Science, Ton Duc Thasng University, Vietnam. His area of research is Materials Science and Manufacturing. Dr. Prakash has authored more than 250 research articles in journals, conference proceedings, and books. In 2018, 2019, 2020, and 2021 he received the Research Excellence Award for publishing the highest number of publications at the University. He is also featured in "World Ranking of Top 2% Scientists" in the 2021 database (Published: 19 October 2021)". He has edited 23 books and three authored books for various reputed publishers like Springer, Elsevier, CRC Press, and World Scientific. He is the series editor of the book "Sustainable Manufacturing Technologies: Additive, Subtractive, and Hybrid, CRC Press Taylor and Francis. He is serving editorial board member of peer reviewer intranational journals "Cogent Engineering" and "Frontiers in Manufacturing Technology". He is serving as Guest Editor of 21 peer-reviewed SCI-indexed Journals. He is an active member of the Institute of Electrical and Electronics Engineers (IEEE), the Institution of Engineering and Technology (IET), and the Indian Science Congress Association (ISCA).

Dr. V. Sambasiva Rao is Professor in the Electrical and Communications Engineering Department in PES University and Director of the Crucible of Research and Innovation (CORI), Bangalore. An engineering graduate from College of Engineering, Kakinada, (Andhra University), he obtained his Ph.D. from BITS, Pilani, and was associated with ISRO in various capacities for 37 years, till his retirement as Deputy Director from ISRO Satellite Centre in June 2011. In ISRO, he was responsible for the development of high bit rate data transmitters for all IRS series of satellites and various RF and microwave systems in S, C, X, Ku and Ka bands for IRS and INSAT missions and was also associated with the planning of communication satellites and development of associated technologies.

Prof. D. V. A. Raghava Murthy is Adjunct Professor & Advisor to Centre for Space Research, Division of Research and Development lovely Professional University, Punjab. Prior to join LPU, Prof Murthy was Director, Aerospace Research in Vel Tech University, Chennai, Tamil Nadu. Apart from that Prof. Murthy worked in ISRO as Systems Engineer after his M.Sc.(Tech) from NIT Warangal and worked on numerous satellite projects, including Bhaskara-II, TES, and IRS satellites. He was Project Director of Cartosat-1, IMS-1, YouthSat, SARAL and first Project Director of Chandrayaan 2. He had also been involved in small satellite projects till 2013, when he became Director of the Earth Observations System in ISRO Head Quarters and was responsible for Earth observing satellites, missions and applications till his retirement in 2016. Additionally, Prof. Murthy started a Society for Small Satellite Systems (SSSS) in 2017 and currently, holding a position of Secretary in SSSS. The society provides a common forum to ISRO and DRDO scientists, academicians, and Industrialists/ executives / start-ups to have discussions and conferences for research, innovations and growth of industry in space technology as well as applications. Under his leadership, several national and international level mega events are organized to uplift the space related activities.

Miniaturized TR Modules for Radar Imaging Payloads: A Review of Materials to Methods for Manufacturability

Vinod S. Chippalkatti and Rajashekhar C. Biradar

Abstract Radar Imaging payload of a satellite has Synthetic Aperture Radar comprising of large number of Transmit Receive modules that form the active elements. These modules essentially have the function of transmitting or receiving the horizontal and vertical polarized signals that generate multipolar beams. To produce reliable and large volumes for onboard use, the need for TR module design to be manufacturable is a critical requirement. In addition, the cost-effective payload requirements combined with weight volume constraints make these modules to be mandatorily miniaturized. The miniaturization uses advances in thermal packaging technologies with judicious combination of attachment and interconnect processes. Starting from the selection of materials with electrical, mechanical, and thermal properties and their suitability for high frequency operations, enhancing the density of electronics for high-reliability performance become the key success factors. This paper presents a detailed review of the materials for manufacturing methods of space grade TR modules.

Keywords TRModules · MMICs · Radar imaging · LTCC · Miniaturization · Ceramic substrates

1 Introduction

Radar technology has significantly evolved over the last four decades, and arrays have seen the paradigm shift from mechanical to electronic steering. These electronically steered beams offer several system advantages. Hence the phased array technology takes the prime spot for space applications. The radar imaging for earth observation using remote sensing techniques is considerably popular.

V. S. Chippalkatti (✉)
Centum Electronics Limited, REVA University, Bangalore 560106, India
e-mail: vinod@centumelectronics.com

R. C. Biradar
REVA University, Bangalore 560106, India

C. Prakash et al. (eds.), *Smart Small Satellites: Design, Modelling and Development*, Lecture Notes in Electrical Engineering 963,
https://doi.org/10.1007/978-981-19-7198-3_1

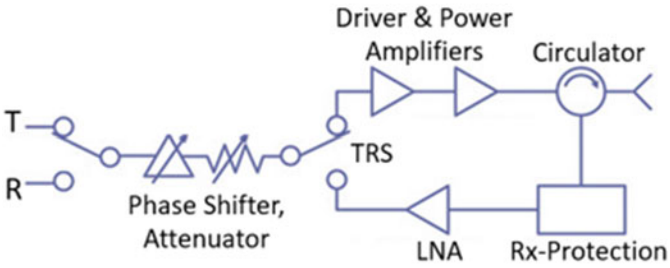

Fig. 1 Basic blocks of a TR module

Transmit Receive (TR) modules are the essential basic building blocks of an active phased array radar. These enable the last stage of amplification for transmitted signals and first stage of amplification for the received signals. They also control the phase and amplitudes of the signals to facilitate the electronic beam steering. The TR modules consisting of RF, digital, power, and mechanical sub-elements, address the structural, thermal, and functional performance of the SAR payload.

A typical TRM, in its common path consists of attenuator, phase shifter, power amplifiers in transmit path, low-noise-amplifier, switching elements, controlling, and limiting elements in the receive path, as shown in Fig. 1.

In an active phased array radar, the TR modules are expected to have higher output power, lower noise figure, desired gain in both transmit and receive paths, optimal pulse rise/fall time, and wider operating temperature. For space applications, the TR modules are generally based on hybrid microelectronics technology which combines active semiconductor devices and passive interconnections within a package. The Synthetic Aperture Radar (SAR) satellite payload hosts hundreds of TR modules controlling the beam steering in azimuth and elevation direction [1]. By controlling large number of radiating elements, each associated with a TR module, the phased array payload can achieve increased range, nano-seconds scan speed, higher accuracy and resolution, and higher system stability [2]. To realize these many space grade TR modules, the design must consider right materials for the best and highly reliable performance and equally importantly, they must be manufactured in a qualified infrastructure using the certified processes by the approved personnel. The processes must be manufacture-friendly for repeatable and reliable delivery of large-scale TR modules. The end criteria should be that the TR modules are cost effective, thermally, and mechanically performing and lightweight. Miniaturization with right packaging techniques for TR modules results in the lightweight and reliable payload for SAR satellites.

The subsequent sections of this paper cover the TR modules packaging criteria, materials selection considerations, different options available, multiple interconnection methods, the need for miniaturization, and comparison of some of the options. The manufacturability and testability aspects of large-scale TR modules for space Radar Imaging payload are also discussed.

2 Packaging Considerations for Space TR Modules

The space grade electronic modules demand more functionality in smaller size, weight, and volume. The packaging solutions for TR modules are expected to be lighter, smaller, more complex operating at higher frequencies and with increased electronic component density. This presents sufficient challenges to RF designers, packaging experts, and materials specialists. All of them need to co-exist and cooperate to realize miniaturized and performing TR modules for space. The general criteria for TR module packaging is described in Fig. 2 [3–6].

The packaging is also implemented in three levels. (1) Device or carrier level, (2) Interconnection board level, and (3) Mechanical housing level. The end objective of all three levels of packaging is to meet the considerations as mentioned above. The integrated TR modules are required to meet the electrical performance comprising power handling, bandwidth, noise figure, minimum reflection, and distortion. The level-1 packaging focuses on thermal conductivity, lower thermal expansion, and hermeticity. The level-2 packaging prioritizes on heat dissipation and mechanical strength aspects. The level-3 packaging results in lighter structure, better mechanical strength, and heat out flow [7]. Figure 3 gives an example of packaging at all 3 levels. In addition to the above, the product engineering for space TR modules necessitates addressing manufacturability and testability aspects.

During the process of packaging design of space TR modules, the following modeling and simulation studies are carried out before finalizing the configuration of the electronic components, attachments, and interconnections. A typical modeling of a wire bond on MMIC chip on a substrate, transmission line modeling of a QFN chip, and thermal analysis model are given in Fig. 4. The coupled-π model method uses inductors with magnetic coupling and capacitive elements as the equivalent circuit model for QFN, the HFSS simulation model elements can be calculated from measured data or EM simulator scattering parameters [7].

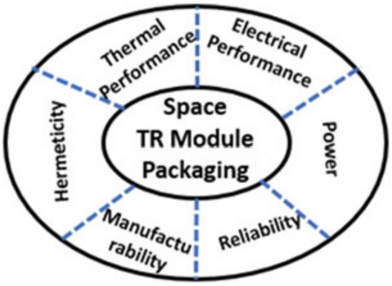

Fig. 2 Packaging considerations for a space TR module [3]

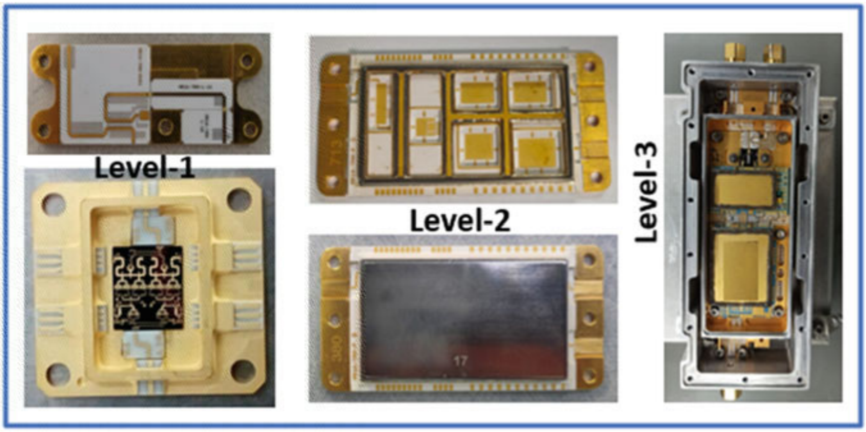

Fig. 3 Multi-level packaging of space TR module

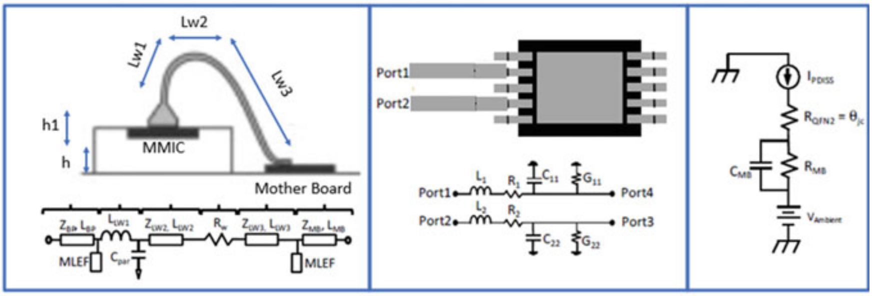

Fig. 4 Modeling for attachments and interconnects

3 Materials for Miniaturization

The choice of materials and their implementation have an immense impact on the TR module performance, size, and reliable functionality. The electrical parameters of the materials comprise dielectric constant, loss tangent, semiconductor dielectric properties, and electrical conductivity of circuit tracks [8]. The mechanical parameters consist of thermal conductivity, thermal expansion, stress, strain, sheer, and young's modulus.

Most of the TR modules are fabricated using ceramics with processes such as thick film, thin film, high temperature cofired ceramics (HTCC), and low temperature cofired ceramics (LTCC) [9–12]. The ceramics in general offer ideal characteristics for hi-reliability packaging and have preferable properties such as high young's modulus resulting in inherent stability, easy wire bond-ability, low losses, high thermal conductivity, and highly reliable microelectronics on ceramics at extreme temperatures. The physical features of the package for TR modules, as also seen in

Table 1 Key packaging materials with their important parameters

Material	Diel const	Loss tangent	Thermal cond (W/mK)	CTE (ppm/oC)
Alumina	9.2	0.003	25	5.4
LTCC (ferro)	5.9	0.0012	2–4	5–8
LTCC (DuPont)	7.9	0.0045	2–4	5–8
AlN (HTCC)	5.8	0.005	150	3.5
Mid/High Tg FR4	4.5	0.018	–	–
Polyamide	4.06	0.006	–	–
Silver (Ag)	–	–	429	19.8
Gold (Au)	–	–	318	14.2
Copper (Cu)	–	–	380	16.5
Aluminum (Al)	–	–	240	22
Tin (Sn)	–	–	67	22
GaAs	–	–	55	5.9

Fig. 3, consist of striplines, microstrips, cavities and several dc, rf and ground layers. For higher frequencies, the package material should be manufacturing friendly to reach superior electrical, mechanical, and thermal performance. Table 1 gives the important parameters of some key dielectrics and packaging materials used in space TR modules at microwave frequencies.

Some of the TR modules use combination of these ceramics. In certain cost-sensitive applications, the printed circuit boards are also used as the carriers. Materials like FR-4 have limited applications for relatively lower frequencies of only a few gigahertz. Laminates with lower dielectric loss and stable properties are preferred over FR-4. Table 2 gives the trends of materials used in space TR modules.

4 Manufacturing Processes

The space TR modules are manufactured in clean rooms of Class-1000 to Class-10000 with all key processes carried out under laminar flow tables of Class-100. A typical miniaturized, chip, and wire type of TR module manufacturing is shown in Fig. 5. The processes are generally classified into attachments, interconnections, and hermetic sealing [13].

The attachment process comprises various attachments for die, substrate, interconnection terminal, and lid. Table 3 provides various attachment processes and materials. The X-ray inspection for void-free attachment ensures reliable thermal performance.

The interconnection process comprises various types of wire bonding and in certain cases soldering of components/connectors. Generally, gold wire bonding of 1 mil dia is popular and meets most of the current requirements. In certain cases,

Table 2 Material trends in space TR modules

Sl no.	Category	Current practices	Improving trends and future
1	Components	Single chip functions. MESFETS, GaAs, HEMT	MCMs, MMICs, Multifunction Core chips, P-HEMTs, HBTs
2	Substrates	Thick and thin film on alumina substrates	HTCC and LTCC substrates, AlN. Substrates as integrated part of the package. 2D/3D packaging
3	PCBs (for lower freq.)	FR4, Hi Tg FR4, RT duroid	High performance laminates, LCPs, MCM-L
4	Mechanical housing	Kovar, aluminum alloys, molybdenum based mechanical housing. hermetically sealed co-axial feed throughs	Integrated Cavities In LTCC, Composites (Alsic), Planar Feed Throughs
5	Connectors	Coaxial connectors	Pressure contacts and RF field couplings, vertical Interconnects

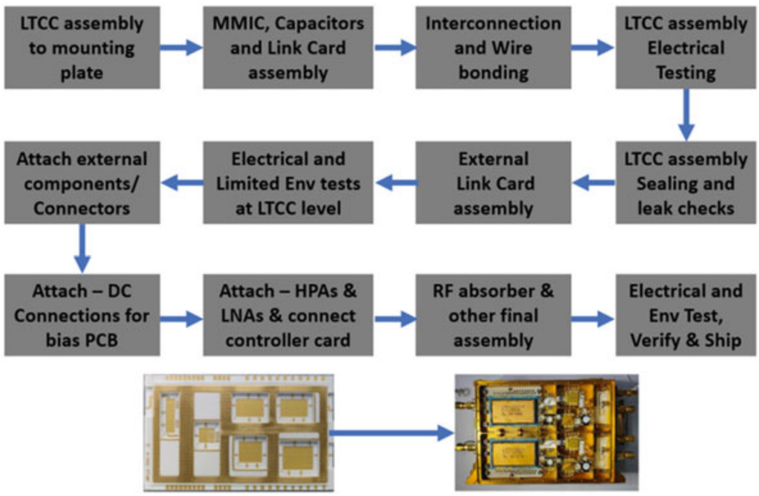

Fig. 5 Manufacturing flow of a typical space TR module

Table 3 Attachment processes and materials

Attachment process	Key characteristics	Materials
Die attach	Lower Cure temperature, higher thermal conductivity, good adhesion strength, lower CTE mismatch between materials attached, excellent shear strength	Solder pastes, Solder preforms, conductive and non-conductive epoxies or films
Substrate attach		
Interconnection Terminal attach		
Lid, Housing attach		

Fig. 6 Space TR module assembly line

multiple gold wire bonds or ribbon bonding is used. TR module production facilities use semi-automatic and automatic wire bonders. Out of the two types of wire bonding, the wedge bonding is preferred to ball bonding for RF applications since the smaller loop height minimizes bond inductance improving the performance of the TR modules.

To achieve the required hermeticity for TR modules, the RF feed throughs, dc-pins, micro-D connectors, and package lids must be sealed. Processes such as solder sealing, seam sealing, and laser welding are followed depending on the size, volume, and materials to be sealed. An important part of the space TR modules assembly line is shown in Fig. 6.

5 Manufacturability, Testability, and Reliability

In the last two decades, for civilian applications, the earth observation techniques using remote sensing have significantly increased. For realizing the large volumes of repeatable TR modules, fully or semi-automated manufacturing lines are needed. Radar imaging satellites across the globe have hundreds of TR modules onboard their payload electronics performing over the satellite mission life. Indian Radar imaging satellites have 576 TR modules in C band in each of the satellites. The Envisat of European Space Agency has 320 modules and Radarsats of Canadian Space Agency have 512 TR modules each [14, 15].

To realize, highly reliable TR modules, the process and the product design teams must work together. The cross-functional team approach with clear focus on manufacturability and testability aspects of TR modules can result in reliable and producible