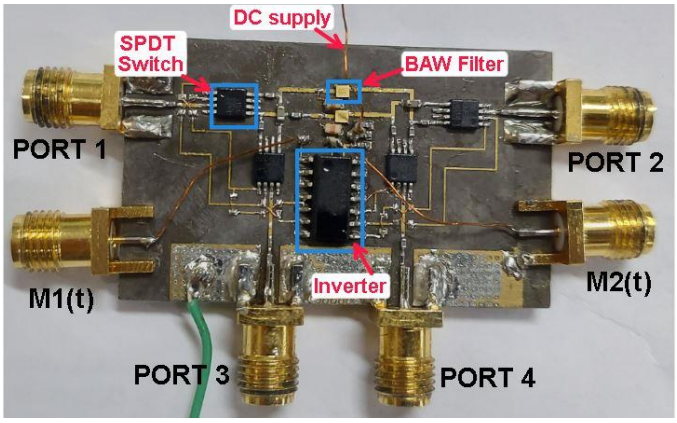
# Executive Summary

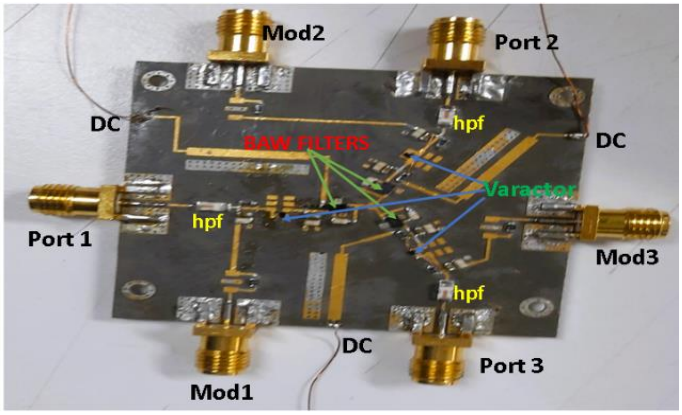
<<Dr.K.C.James Raju>>
<<Senior Professor, Centre for Advanced Studies in Electronics Science & Technology,
School of Physics, University of Hyderabad, Hyderabad- 500046>>

1. **Title of the Project:** Development of integrated miniature magnet-free microwave circulator
2. **Date of Start of the Project:** 01.10.2021
3. **Aims and Objectives:** Design and development of miniature magnet-free microwave circulators using Varactors and Resonators.
4. **Significant achievements (not more than 500 words to include a List of patents, publications, prototypes, deployment, etc)**
   a) Two designs of magnet-free microwave circulators are realized in Microwave Integrated Circuit (MIC) Technology using off-the-shelf discreet components, and they were tested and demonstrated the circulator responses.
   b) Using ferroelectric thin film-based reactors and Resonators, the above designs can be further miniaturized in Microwave Monolithic Integrated Circuit (MMIC) Technology. For that, the Varactors and HBAR resonators are realized. Most of the process steps for FBAR resonators have also been completed. The design for the monolithic realization with these resonators and Varactors has reached its final phase. It can be frozen only after seeing the results of some of the ongoing MIC realizations.
   c) Using their successful devices, A Fab-compatible design is being worked out using the Process Design Kit (PDK) of GAETEC, Hyderabad. Once it is completed, a formal proposal will be submitted to GAETEC with proposed DRDO funding to realize these devices in the GAETEC foundry. Once that is done, these devices will be industry-ready. At least 2 cycles of test runs are required. This was not the original objective but became possible with the insights garnered over the last 3 years.
   d) A breakthrough is achieved in bringing down the crystallization temperature of these ferroelectric thin films from 700° C to 250°C. It was done through Laser

Induced Crystallization. This lowering of temperature made these active oxide films compatible with a wide range of substrates and processes hitherto not possible.




(a)




(b)

Photograph of fabricated devices (a) Four port magnet less circulator using sequentially switched delay line technique (b) Three port circulator using angular momentum biasing technique

5. **Concluding remarks:** This Fellowship is an extremely commendable initiative that needs to be highly appreciated. This great morale booster makes us work to make the impossible possible. The work was planned with a 5-year duration in mind, as 3 years is too short for such challenging objectives to be met. Within 3 years, the progress made is commendable. If 2 more years are granted, the remaining objectives also could be achieved.

## Patents Awarded:

1. J.P.Goud**, K.C.James Raju** et.al, "**A laser-based method to crystallize ferroelectric thin films at sub 300ºC temperatures and demonstration of its application by realizing tunable microwave devices on substrates that are crystalline and amorphous**." Patent Awarded. Patent No. 499324. Awarded on 27.2.2024. Filed on 27/02/2019.
2. Provisional Patent filed: Title: "**Fabrication of microwave varactors on polymer substrates using low-temperature crystallized ferroelectric thin films"**, Inventors/Authors: Akhil Raman T S, Chedurupalli Shivakumar, **K.C. James Raju**, Application Number: 202241032453, Application Date: 7-June-2022.

## Prestigious Awards/ Honors Received:

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| Elected Sr.Member, IEEE | IEEE | 2019 |
| Elected Fellow of the Institution of Electronics & Telecommunication Engineers | IETE | 2021 |
| Awarded Abdul Kalam Technology Innovation National Fellowship | DST-SERB/ INAE | 2021 |
| Visitor's (President of India) Award for Technology Development | Rashtrapathi Bhavan | 2023 |
| Institute of Physics Fellow (IOP) | UK & Ireland. | 2024 |

## Publications

1. Shivakumar Chedurupalli, Lalitha S, Abhilash T, and **James Raju K.C,** "Magnet-Free Circulator Using BAW Filters Based on Spatiotemporal Modulation for Full-Duplex Applications", IEEE MAPCON 2024**.** To be presented.
2. K. S. S. Sravya, S. Chedurupalli and **K. C. James Raju**, "Magnet-less Circulator with Bulk Acoustic Wave Filter Delay Elements," *2023 IEEE Microwaves, Antennas, and Propagation Conference (MAPCON)*, Ahmedabad, India, 2023, pp. 1-4, doi: 10.1109/MAPCON58678.2023.10463972.
3. S. K. Nath, J. P. Goud, S. S. Kongbrailatpam, G. Rajaram and **K. C. J. Raju**, "A Highly Tunable Barium Strontium Titanate Thin Film MIM Varactor With Floating Metal," in *IEEE Microwave and Wireless Components Letters*, vol. 31, no. 12, pp. 1283-1286, 2021, doi: 10.1109/LMWC.2021.3110981.
4. J.P. Goud, A. Kumar, K. Sandeep, S. Ramakanth, P. Ghoshal, **K. C. J. Raju**, Tunable Microwave Device Fabrication on Low-Temperature Crystallized $Ba_{0.5}Sr_{0.5}TiO_3$ Thin Films by an Alternating Deposition and Laser Annealing Process. *Adv. Electron. Mater*. 2021, 7, 2000905. https://doi.org/10.1002/aelm.202000905

5. S. S. Kongbrailatpam, J. P. Goud and **K. C. J. Raju**, "The Effects of a Coated Material Layer on High-Overtone Bulk Acoustic Resonator and its Possible Applications," in *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 68, no. 4, pp. 1253-1260, 2021, doi: 10.1109/TUFFC.2020.3025618.
6. J. Pundareekam Goud, Ajeet Kumar, Mahmoud S. Alkathy, Kongbrailatpam Sandeep, Akhil Raman TS, Bibhudatta Sahoo, Jungho Ryu, **K.C. James Raju**, "Thickness dependence of microwave dielectric tunability in Ba0·5Sr0·5TiO3 thin films deposited by pulsed laser deposition", Ceramics International, Volume 49, Issue 1, 2023, Pages 1188-1194, ISSN 0272-8842, https://doi.org/10.1016/j.ceramint.2022.09.095.
7. S. Chedurupalli, S. Bhanu Prakash, T. S. Akhil Raman, K. R. Kumar and **K. C. James Raju**, "Porous silicon based Bulk Acoustic Wave device using Barium Strontium Titanate thin film," *2022 IEEE International Symposium on Applications of Ferroelectrics (ISAF)*, Tours, France, 2022, pp. 1-3, doi: 10.1109/ISAF51494.2022.9870155.
8. S. Chedurupalli, K. Karthik Reddy, T. S. Akhil Raman and **K. C. James Raju**, "High Overtone Bulk Acoustic Resonator with improved effective coupling coefficient," *2022 IEEE International Symposium on Applications of Ferroelectrics (ISAF)*, Tours, France, 2022, pp. 1-4, doi: 10.1109/ISAF51494.2022.9870132.
9. S. S. Kongbrailatpam, J. P. Goud, **K. C. J. Raju** and G. Pillai, "Low Temperature and DC Bias Dependence Study of Barium Strontium Titanate Based High Overtone Bulk Acoustic Resonator (HBAR)," *2022 IEEE International Conference on Emerging Electronics (ICEE)*, Bangalore, India, 2022, pp. 1-4, doi: 10.1109/ICEE56203.2022.10117931.
10. Chedurupalli Shivakumar, Akhil Raman T S, Kooriyattil Sudheendran, **James Raju K C** "Fabrication and Characterization of Tunable Varactors Using Barium Strontium Titanate Thin Film", P-116, ICEE, International Conference on Emerging Electronics, ICEE 2022.
11. Raman T. S., Akhil, Shivakumar Chedurupalli and **James Raju K. C**.. "Low-temperature crystallization of BST thin films on RT/Duroid substrate for tunable microwave devices." *International Workshop on Thin Films for Electronics, Electro-Optics, Energy and Sensors* (2023). DOI:10.1117/12.2645993
12. S. S. Kongbrailatpam, A. R. T S, C. L N, **K. C. J. Raju** and G. Pillai, "Laterally Coupled BST/Sapphire High Overtone Bulk Acoustic Resonators Exhibiting DC Tunable Comb Filter Response with High Q.f Product," *2023 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFCS)*, Toyama, Japan, 2023, pp. 1-3, doi: 10.1109/EFTF/IFCS57587.2023.10272122.
13. K. S. Sharma, A. Raman T.S, C. L. N, **J. R. K. C** and G. Pillai, "Temperature and Bias-Dependent Switchability and Tuneability of Very High-Quality Factor GHz Resonators," *2024 IEEE 37th International Conference on Micro Electro Mechanical Systems (MEMS)*, Austin, TX, USA, 2024, pp. 148-151, doi: 10.1109/MEMS58180.2024.10439480.