Study and Realization of Microwave & Millimeter-wave Circuits using Substrate Integrated Coaxial Line Technology (SICL)

A Thesis submitted by

Idury Satya Krishna

in partial fulfillment of the requirements for the award of the degree of

Doctor of Philosophy

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Indian Institute of Technology Jodhpur
Department of Electrical Engineering

April 2022

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Conclusions and Future works

The thesis presents a detailed study of a new technology named substrate integrated coaxial line (SICL). SICL technology takes advantage of PCB fabrication techniques to synthesize traditional coaxial line as a low profile planar rectangular coaxial line. Furthermore, this thesis explores numerous possibilities for SICL based circuits to replace the currently used planar microwave/millimeter technologies in the present and next generation wireless systems. Firstly, the basic working principle of substrate integrated coaxial line and its application has been reviewed. A detailed discussion on the design of SICL transmission line is carried out and a closed form equation of the characteristic impedance of SICL line as a function of its physical and electrical parameters has been derived. The salient point of this study was the identification of the optimal width of outer conductor to thickness of substrate (W_{out}/H_{sub}) ratio to utilize the coaxial nature of SICL. Robustness of the proposed formula has been confirmed through testing of the fabricated SICL line with different dielectric constant and thickness. The self-packaged SICL requires an external transition for testing and integration with other planar transmission line. A wideband coaxial to SICL transition has been implemented as a male to female connection seen in coaxial connections. Furthermore, a novel topology to facilitate a transition from microstrip line to SICL without the need for any blind via is analyzed and experimentally verified up to 40 GHz with return loss better than 14 dB and a maximum insertion loss of 1.78 dB (19 dB bandwidth up to 20 GHz with insertion loss less than 0.71 dB). A new SICL based wideband transition to isolate DC bias circuitry required for active circuit integration in system design is proposed for X-band. The transitions proposed in this thesis provide seamless integration between SICL technology and other planar and non-planar technologies.

This thesis with focus on design and development of SICL based circuits covers various new techniques to improve the performance of the microwave and millimeter-wave bandpass filters. Novel designs for bandpass filters with wide bandwidth, high selectivity, good out of band rejection in a compact form factor has been designed, fabricated and experimentally validated. A study on dual-mode SICL based bandpass filter operating at 28 GHz has been carried out. The proposed filter demonstrated the capability to excite the degenerate modes in the square-shaped inner conductor of the SICL section. Furthermore, using cross-shaped slots of unequal widths and lengths a dual-mode response at 27.365 GHz has been achieved. The proposed SICL cavity occupies only 53.2% area as compared to a SIW cavity. Bisecting the virtual magnetic wall of proposed SICL cavity half-mode and quarter-mode based bandpass filters in SICL technology have been studied and realized in this thesis for enhanced size reduction. Two bandpass filter operating at 28 GHz with multiple transmission zeros has been demonstrated through full-wave simulation in HFSS. A mode chart to determine the resonant frequency of fundamental as well as higher order modes of the proposed SICL cavity and its half mode has been shown. In the designed filter, the frequency selectivity is enhanced by a pair of transmission zeros on each lower and upper side of the passband. In addition, a new SICL filter integrated with band-reject resonators for extended out of band response possessing controllable transmission zeros is devised with simple design procedure. The proposed SICL filters ($filters\ A$ and B) exhibit a 14.21% & 11.64% 3-dB fractional bandwidth respectively, with good out of band performance in a compact size. As a proof of concept the proposed filter bandpass without any embedded resonators (filter A) is designed with center frequency at 10 GHz. The experimental validation of proposed filter affirmed a fractional bandwidth of 4.54% with 3-dB passband of 450 MHz centered at 9.91 GHz (f_o). The superior integration capability with planar circuits and broad monomode TEM operation advocates the utilization of proposed SICL based bandpass filters in millimeter-wave range. Another bandpass filter using the low-loss, shielded and wideband transmission properties of SICL is implemented to realize a dual-mode SICL based dual-bandpass filter with widely spaced passbands located in X and K-band. The flexible filtering response has been attributed to the simple topology proposed for single-band and dual-band operation. The SICL based dual-band filter using inter-coupled quarter-mode cavities is designed, fabricated and tested to confirm the proposed filter synthesis. A novel perturbation technique has been explored for SICL based ring resonator to implement a completely shielded dual-mode bandpass filter with low insertion loss for K_u-band. The outer conductor formed by lateral vias in SICL is utilised to excite the degenerate modes. The measured results of the fabricated prototype indicated low insertion loss of 1.18 dB with 2.6% FBW centred at 13.83 GHz. The research work on bandpass filters was completed with a demonstration single layer implementation of a coaxial resonator and its study on three filters with enhanced bandwidth and multiple transmission zeros exhibiting high degree flexibility to improve selectivity as well as out of band rejection. Further, the adjustable bandwidth and independently tunable transmission zeros to design as per user requirement for K_u-band are the notable features of the proposed single layered coaxial bandpass filter. Three experimental prototypes are developed and tested to show a FBW better than 23% in a size less than $0.5\lambda_g^2$. The electromagnetic shielding capability of the proposed bandpass filter along with its size reduction makes it a highly desirable candidate for millimeter-wave applications. The proposed technique can be extended to develop passive and active microwave/millimeter-wave components with inherent filtering characteristics. Use of SICL as planar guiding media for filter design aids in building a RF-front end architecture where small form factor is preferred for installation in modern hand-held devices and access points.

In addition, this thesis investigates design and implementation of three and four port network in SICL technology for various applications. SICL based baluns for wide-bandwidth and dual-band operations are proposed. Firstly, three-port SICL based baluns for wide-bandwidth and dual-band operations has been proposed. The design of two SICL based wideband baluns has been presented and analyzed for operation in the K-band (18-26 GHz). The SICL based planar balun operates for a frequency range 17.9 GHz to 26.85 GHz with low amplitude and phase imbalance. The planar SICL balun occupying a lateral footprint of only $0.73\lambda_g \times 0.75\lambda_g \times 0.05\lambda_g$ is fabricated and experimentally validated. Another folded wideband balun is studied which occupies only 58% lateral area as compared to the proposed planar balun SICL balun. This size reduction comes at the cost of the fabrication complexity. In both these configurations, lateral vias along with top and bottom ground plane form a shield to prevent unwanted coupling with neighboring circuits, thereby exhibiting good electromagnetic compatibility. Another interesting use case of SICL technology has been explored in design and development of dual-band balun operating at 6 GHz and 28 GHz to cover the microwave and millimeter-wave bands of 5G application. After extensive analysis, the SICL based dual-band balun is realized using PCB fabrication techniques. The measured results indicated frequency range 5.1 GHz to 6.3 GHz and 26.5 GHz to 27 GHz magnitude imbalance better than $|S_{21}|$ - $|S_{31}|$ = $\pm$ 1.5 dB and phase imbalance better than $\angle S_{21}$ - $\angle S_{31}$ = $\pm$ 2.8°. The complete modeling including depiction of electric field distributions, circuit and full-wave simulated S-parameters has been shown to support the proposed design methodology. The ability of SICL technology to realize components in compact size with excellent out of band rejection has been demonstrated through design of a quadrature hybrid. Performance of the proposed quadrature hybrid is experimentally verified up to 20 GHz and found to be in accordance with the simulation. Further, the dependence of transmission zero on the length of open-ended stub is studied and verified through simulation. The designed quadrature hybrid achieves a compact size of $0.10\lambda_g^2$ with 12.24% fractional bandwidth centered around 10 GHz. The superior integration capability with planar circuits and robust electromagnetic shielding motivates the use of proposed SICL based quadrature hybrid. Another integral RF-front end component that has been studied in this thesis is a compact dual-broadband millimeter-wave rat-race coupler. The proposed SICL based rat-race coupler realized using planar coaxial stubs has been analyzed and analytically derived closed form expression are derived to design the coupler in the range of realizable frequency ratios. The working principle of the proposed coupler is confirmed by testing the fabricated rat-race coupler prototype. A measured FBW of 26.69% and 10.41% centered at 10.83 GHz and 23.15 GHz respectively was observed. The proposed dual-broadband SICL rat-race coupler has low amplitude and phase imbalance with spurious rejection better than 22 dB up to 40 GHz. In this thesis the study of a wideband crossover developed using substrate integrated coaxial line (SICL) technology is presented. The proposed SICL-based crossover isolates the two physically overlapping channels by routing the signal in a middle conductor of SICL through the transmission line created in the top and bottom ground plane using a metalised blind via. An equivalent model is developed to understand the role of substrate height in the proposed SICL based crossover. The design methodology is affirmed by fabricating and testing the experimental prototype. The measured results show isolation between channels are more than 19 dB with better than 18 dB return loss and less than 1.2 dB insertion loss from 0.2 to 20 GHz. The non-dispersive nature of SICL line and simplistic design technique with minimal discontinuities the designed crossover helps in achieving low peak-to-peak group delay variation, less than 0.04 ns over the entire bandwidth. The SICL-based crossover developed using the proposed design principle enjoys wide unimodal bandwidth covering L, S, C bands and other prominent higher X and K_u bands simultaneously. Later in this thesis, the design and fabrication of wideband branch-line coupler & two-stage wilkinson power divider covering the entire *Ku*-band with application in six-port receiver architecture has been studied and discussed in detail. Use of compact size and electromagnetically robust three and four port passive components designed in SICL technology aids in building exceptional front-end communication system.

Finally, this thesis deals with the study and realization of multi-functional integrated SICL based components. An SICL filter-antenna operating at 25.45 GHz has been realized by integrating a slot antenna with 5^{th} order parallel coupled $\lambda/2$ SICL resonators. This multi-functional component demonstrating both radiating and filtering function. The initial design comprised of a 5^{th}-order bandpass filter designed and fabricated in SICL based technology. The filter synthesis is affirmed by fabricating an experimental prototype. The measured results of proposed SICL bandpass filter demonstrates an insertion loss of 1.96 dB at the center frequency 28 GHz with a 3-dB fractional bandwidth of 14.03%. A technique to integrate slot antenna over the filter has been proposed to realize the filtering antenna. The peak gain of co-designed filter-antenna is better than 4.8 dBi at 25.45 GHz with good selectivity. Instead of cascading the front-end components, proposed co-design approach in SICL technology maintains compact size as the slot antenna is situated over filtering element and eliminates the need for any interface between filter & antenna. The proposed SICL filter-antenna serves as a good candidate for millimeter-wave transceivers due to its compact size and self-packaged structure. Further, the study, design and development of a highly selective diplexer with excellent isolation owing to the multiple transmission zeros of the synthesized bandpass filters has been proposed. The SICL diplexer in this work utilized two SICL based bandpass filters and an impedance matching network. The experimentally validated prototype of the diplexer indicated low insertion loss of 1.33 dB and 1.58 dB at the center frequency 11.2 GHz and 13.8 GHz respectively, with out of the rejection up to 20 GHz. The self-shielded structure of SICL and multiple transmission zeros outside the band of operation provides a high measured isolation greater than 45 dB at both transmit and receive bands of the proposed diplexer. A wideband high gain linearly tapered antipodal antenna fed by GCPW line covering a frequency range of 11 GHz to 18 GHz has been realized for integration with the proposed SICL diplexer. The working of the SICL diplexer-antenna integrated system has been affirmed by recording the gain of the peak value of 13.8 dBi and 13.15 dBi at 11.21 GHz and 13.85 GHz, respectively in an anechoic chamber. The integration of the proposed diplexer with a high gain antenna is of immense interest in design of commercial RF front-end. Finally, using the wideband branch line coupler and wideband wilkinson power divider a completely self-packaged and self-shielded SICL based six-port module was designed, fabricated and experimentally validated. The proposed wideband six-port network works over the entire K_u band with low group delay & is realized in a compact form factor. A measured return loss and isolation better than 10 dB at the input port of the compact wideband six-port network and the measured transmission from RF and LO port to output ports is within an imbalance of ± 1.6 dB over the entire range of 12 GHz to 18 GHz has been achieved.

Overall this thesis presents the detailed study of a variety of components used in the modern RF-front end such as transitions, bandpass filters, baluns, quadrature hybrid, 180° couplers, crossover, and antennas. Further, the realized SICL components demonstrates the advantages of SICL technology in implementing microwave/ millimeter-wave components in a compact form factor with low-loss propagation, and ease of integration to design various RF front-end components with enhanced functionalities.

6.0.1 Future Scope of Work

The thesis presents a detailed study of several SICL technology based indispensable components that are widely used in building the modern day RF-front end. Novel SICL based transitions with wide-bandwidth and DC blocking capabilities and bandpass filters in compact size with wide-bandwidth, high selectivity, dual-band operation and with enhanced flexibility in adjusting the filtering response have been explored in this work. Furthermore, baluns, quadrature hybrid, 180° couplers, crossover, multi-functional filtennas, diplexer-antenna system and six-port network with enhanced functionalities has been studied in this thesis.

The research conducted in this thesis opens up new possibilities for investigations in the following directions:

1. **Multi functional RF front-end components:** The proposed thesis has examined design of multi-functional components such as filtenna that encompasses radiating and filtering functionalities and coupler with extended out of rejection due to filtering capabilities. However the investigation carried out in this opens the scope for exploring several other multi-functional components to reduce the overall size and cost of the system. It will be attractive in commercial standpoint to have self-duplexing antennas, filtering amplifiers, self-oscillating mixers, self-biased sensors with the help of ambient RF energy harvesting to design highly efficient RF front-end.

2. **Design of Antennas and arrays:** Utilization of SICL technology in antennas and antenna array reduces the feed network losses and minimize the mutual coupling between elements of array. Furthermore, the compact SICL based cavity proposed in thesis for filter design can be extended for design and development of cavity backed antennas with unidirectional radiation pattern and enhanced functionalities. Such antennas are of immense interest in high capacity millimeter-wave links.

3. **Integrated RF front-end:** The bias lines and intermediate connection between transistor and matching network of active circuits when designed in the completely shielded SICL offers low loss and excellent signal integrity. Furthermore, the low-loss technique proposed for integration of SMD components with SICL to preserve the self-shielding in this thesis will serve as an important stepping stone for realizing hybrid active circuits using SICL technology with externally mounted transistors and passive components. This thesis also covers the design of passive components such as filters, couplers using the high Q and low loss resonator that facilitates design in compact size with wide-monomode TEM based characteristics. As future work it will be interesting to explore the seamless integration offered by SICL technology to design a compact microwave/ millimeter-wave transceiver systems.

4. **Reconfigurability:** The need for lower loss and better performance is pushing towards utilization of high-Q transmission lines. But inevitably with higher Q the bandwidth of cavity based filters and antennas are reduced. As observed from the work carried out for millimeter-wave bands in thesis, often due to the fabrication tolerance a slight deviation in the center-frequency and bandwidth is observed. As future work it will be interesting to include tuning elements such as varactor diode to compensate for the post-fabrication errors and fine tune the component response as required. Also such tunable components minimize cost and efforts due to repeated fabrication to achieve the desired results. Also tunable holds great significance to simultaneously to serve multiple bands in the spectrum. Another dimension to explore could be design of bandpass filters with dynamically adaptive transfer function to facilitate switching between bandpass to bandstop and low pass filtering function. Such components find applications in utilization of densely allocated spectrum to kill in-band & out of band jammers with dynamic interference suppression.

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