Substrate Integrated Coaxial Line (SICL)- A new frontier for 5G millimeterwave communication

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Over the years, millimetre-wave (mm-wave) spectrum (30-300 GHz) has been considered a puzzling solution with lots of potential capabilities by the researchers. Since the early experiment by Prof. J. C. Bose during 1894-96 at University of Calcutta, several studies of this spectrum exhibit both pros & cons. e.g. wide bandwidth, high speed communication along with higher atmospheric absorption, higher path loss. Recently, with the advent of 5G technologies, industry and academia have started looking for newer spectrum for future technologies since the microwave bands have been congested with existing applications. The spectrum above 24 GHz offers as a potential candidate for future high-speed solutions with ultra-wideband unlicensed spectrum. The 3GPP working group in their Release 15 has identified 24 GHz, 26 GHz, 28 GHz and 38 GHz as potential candidate for future 5G mm-wave communication. In addition, WiGig (60 GHz), Automotive and Industrial RADAR (77 GHz), 94 GHz RADAR application have been proposed by the researchers for future high speed connected solutions. All these standards open up lots of future application e.g. enhanced multi-Gbps mobile broadband (eMBB), ultra-low latency mission critical application, massive machine to machine communication, cellular V2X (C-V2X) communication, indoor 60 GHz WiFi, industrial IoT (IIoT) application etc.

Realizing communication systems for commercial application at mm-wave spectrum is a challenging task since the conventional planar technologies exhibits serious drawback at these frequencies. The planar technology e.g. microstrip, CPW, slot line is widely used in microwave frequency ranges for implementing circuits and systems for handheld and user personal digital assistant (PDA). However, at mm-wave frequencies, such technologies suffer from radiation loss, surface wave loss, conduction loss. The conventional waveguide based transceiver systems are typically used at these frequencies which are bulky in nature and not suitable for customer premises equipment (CPE). Therefore, a new kind of planar solutions suitable for mm-wave frequency is of prime interest among the researchers. Besides, the communication link at mm-wave frequencies requires additional measures for successful transmission. Due to very small wavelength (in the order of millimetre), the path loss at these frequencies are comparatively high. To mitigate such challenges, narrow beamwidth pencil beam high gain radiation pattern is generally preferred. Besides, to enhance coverage of the beam, beam steering antenna or multibeam antenna is generally preferred at mm-wave frequencies. Therefore, a detailed study of beam forming network and antenna array feed network along with high performance filter, coupler, power divider is of prime interest among the industry and academia.

Coaxial Line is one of oldest known technology which exhibits satisfactory performance from DC- 100 GHz. Although the technology is non-planar in nature, the wideband monomode bandwidth and non-dispersive characteristics makes it an attractive candidate for mm-wave applications. Recently, a planar form of the coaxial line technology has surfaced named as "Substrate Integrated Coaxial Line (SICL)" where rectangular coaxial structure is implemented in planar substrate. The technology utilizes double layer conventional copper cladded dielectric substrate whose top and bottom metallic plate along with rows of metallic vias creates outer conductor which along with middle planar strip creates coaxial environment as shown in Fig. 1. The self-shielded TEM based line along with low profile planar form is one of the promising candidate for future mm-wave communication systems. It helps to realize interconnection between active component along with high Q filters, diplexers which are basic building block to design full transceiver system in complete planar form. The synthesis of conducting sidewall in planar substrate is implemented by placing rows of metallic vias which are typically realized by plated through hole (PTH) process. The artificial via fence boundary can mimic the original non planar shielded wall if the diameter (d) and pitch (s) of the vias maintain certain design criteria. The diameter (d) of the via typically should be kept within one fifth of the guided wavelength and the pitch should be selected less than twice of diameter of the via such that the via wall is able to guide the electromagnetic wave through the line. The width of the SICL can be determined by studying the mode propagating through the line. The dimension of the SICL should be chosen such that the cut off frequency of the first higher order mode TE_{10} should be well above the operating frequency so that a monomode operation can be ensured in the frequency of interest. The cut off frequency of TE_{10} mode is typically decided by analysing the SICL as a synthesized dielectric filled waveguide. By selecting a suitable width of the SICL, the cut off frequency can be pushed to the very high frequency ranges well above the operating bandwidth. Once the outer conductor dimension is defined, the inner conductor dimension of the SICL can be determined by choosing an appropriate width of the middle strip to keep the characteristic impedance of the line at the desired level.

To develop SICL based mm-wave transceiver systems, transition/ interconnect from SICL to other technologies is required. The transition design also helps in measurement of SICL based devices. The transition between microstrip to SICL is shown in Fig. 1. The interconnect facilitates connection of commercially available SMA launchers to the SICL section for characterization of device under test. The design demonstrates a wideband microstrip to substrate integrated coaxial line (SICL) planar transition for mm-wave applications. The transition operates between DC-40 GHz with return loss better 14 dB and...
insertion loss less than 1.78 dB. It utilizes gradual modification of boundary condition at the junction of microstrip and SICL so that the smooth transition from quasi-TEM to TEM field distribution is realized. The introduction of slotted top conductor helps to orient the field from middle layer to either half of the top conductor while preventing the horizontal component of the field to exist as shown in Fig. 1. This helps to slowly generate radially outward field configuration as required in SICL and the TEM mode is excited in the SICL section.

Recently, SICL based circuits working in mm-wave frequency have also been reported. A K band (18-26 GHz) SICL power divider is shown in Fig. 2. The 1 to 4 power divider exhibits equal power division with power and phase imbalance within 0.6 dB and 10° respectively. The design principle can be extended for implementing SICL based large antenna array feed network. The self-shielded SICL section can be used to realize high Q resonator and filter. A mm-wave SICL resonator based filter is shown in Fig. 2. The resonator is realized by short circuiting two ends of a wide SICL section. The SICL half mode resonator concept is used in the filter by realizing perfect magnetic conductor (PMC) boundary diagonally and thus multiple resonator is designed within a compact form factor. By properly exciting these two resonators, the proposed low insertion loss SICL filters exhibit 14.21% 3-dB fractional bandwidth and a good out of the band performance with rejection level better than 20 dB in both below and above the passband. Utilization of compact size and electromagnetically robust filters designed in SICL technology provide notable front-end millimetre-wave communication system. Another aspect of the SICL section is its wideband TEM mode operation which can be utilized to support different spectrum. The 5G communication is expected to rely on multiple spectra ranging from microwave to mm-wave broadly divided into two groups – sub-6 GHz spectrum and mm-wave spectrum. Therefore, single technology supporting both the bands is of prime interest for successful implementation of 5G standards. A dual band SICL balun working in both the bands is demonstrated in Fig. 2. The design replaces quarter wave section with Tee section. By properly choosing characteristic impedance and electrical length of the Tee section, the operating bands can be tuned. The presented design covers frequency ranges 5.7 GHz to 6.8 GHz and 27.12 to 28.22 GHz with better than -19 dB return loss, ±0.5 dB amplitude imbalance and ±2° phase difference. Fractional bandwidth of 17.6% and 3.97% at 6 GHz and 28 GHz band respectively is achieved by the proposed balun covering 0.43λg × 0.68λg circuit area.
The SICL can be also used to design mm-wave antenna and its array. The SICL resonator can be utilized to realize cavity backed slot antenna where the SICL resonator at the backside of the slot helps to generate unidirectional radiation pattern with high gain. A design of mm-wave SICL cavity backed slot antenna is shown in Fig. 3. The slot is placed at the top conductor of the cavity which disturbs the surface current distribution of the cavity and thus the slot is excited by the dominant TEM mode of the cavity. The measurement results show a gain of 5.6 dBi at 28.6 GHz and high front-to-back ratio better than 17 dB. The proposed antenna exhibits FBTR of 17.36 dB and co-pol to cross-pol ratio of 28 dB. This antenna can be used for mobile handheld devices, other 5G user equipment and further be used as the basic element for implementing antenna array for future 5G applications. For establishing mm-wave communication link, high gain large antenna array is generally required. A SICL based high gain planar antenna array is shown in Fig. 3. In the design, a short-circuited SICL line is used to feed slot array antenna placed at top and bottom conductor. The use of feedline as backside reflector for each antenna element helps to realize a compact dual beam high gain antenna array. The low profile 6X4 C shaped slot array operates at 25.16 GHz with 3 dB beamwidth 46° and a gain of 9.87 dBi. The antenna is fed by SICL 1 to 4 power divider and is realized in a single planar substrate. Such antenna array with dual beam is a suitable candidate for mm-wave wireless access point with wide coverage in azimuth space.

A broad study of SICL based low profile mm-wave components has been presented here. All these components can be used as basic building block for designing low-cost high-performance transceiver or tracking radar network. Such systems find application in healthcare, transport, logistics where huge amount of data transfer can be facilitated by means of such multibeam high gain antenna-based mm-wave communication system.

References


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