Magnet-Free CMOS Passive Circulator Based on Spatio-Temporal Conductivity Modulation with >1W Power Handling and Loss-Free Antenna Tuning Across 1.85 VSWR

Aravind Nagulu[(1)], Andrea Alù[(2)] and Harish Krishnaswamy[(1)]
(1) Columbia University, New York, NY 10027, USA
(2) CUNY Advanced Science Research Center, New York, NY 10031, USA

Wireless systems that can simultaneously transmit and receive (STAR) have been drawing significant attention in the recent literature. STAR functionality is critical for radar systems and full-duplex wireless, in which a circulator is a crucial component. Non-reciprocal components are traditionally implemented using magnetic (ferrite) materials, making them bulky, expensive and not suitable for applications demanding low C-SWAP (cost, size, weight and power). A chip-scale/CMOS non-magnetic circulator has been presented for the first time based on staggered commutation of N-path filters (N. Reiskarimian & H. Krishnaswamy*, Nature Comm.* 2016). However, the requirement of low duty-cycle clocks forces the usage of high-speed, short-channel devices, and hence is plagued by low power handling. Furthermore, in a circulator transmitter-to-receiver isolation is typically limited by reflections at the antenna port, rather than by the inherent isolation of the circulator. Antenna impedance is dynamic and susceptible to variations due to changes in the surrounding environment. This necessitates an on-chip antenna balancing mechanism to maintain isolation.

Here we demonstrate a 1GHz circulator in 180nm SOI CMOS that addresses these challenges. Ultra-broadband non-reciprocity is achieved by sandwiching a differential transmission line between two Gilbert-quad switch sets, similar to our 25GHz implementation (T. Dinc, et al., *Nature Comm.* 2017*)*. With an appropriate choice of length of the transmission line and synchronization between modulation clocks, ultra-broadband phase non-reciprocity, specifically gyrator functionality, can be achieved. A highly-linear circulator is then realized by wrapping a transmission line around the ultra-broadband gyrator and strategically placing the ports such that the transistors in the gyrator experience very low voltage swing for transmitter port excitations. A key feature of the gyrator architecture is that it allows modulation at a sub-harmonic of the operating frequency, enabling the use of high-voltage thick-oxide switches to enhance linearity and power handling. We also demonstrate a loss-free, inductor-free antenna balancing concept that uses the inherent 90^o phase shift within the circulator from the transmitter to the antenna port to accomplish comprehensive antenna balancing across the complex impedance plane. Tunable reactive impedances from the transmitter and the antenna port to the receiver port are able to cancel both real and imaginary parts of transmitter-to-receiver isolation in the presence of finite antenna VSWR. Furthermore, we exploit the differential nature of the circulator to realize both lead and lag feed impedances by just using capacitors. Tuning capacitors were implemented using switched capacitor banks with aggressive transistor stacking, in order to achieve high-linearity and high power-handling capabilities. Through these innovations, the realized circulator achieves a transmission loss of 2.1dB/2.9dB for TX-ANT/ANT-RX paths. The measured TX-ANT input P1dB is >+30.66dBm (limited by the measurement setup), at which point the compression is only 0.66dB, TX-ANT/ANT-RX IIP3s are +50.025dBm/36.9dBm. ANT-RX NF is 3.1dB. A comprehensive coverage of 1.85:1 VSWR has been observed with an average degradation of ($S_{21}+S_{32}$) of 0.4dB. The averages of the 20dB, 30dB and 40dB isolation bandwidths inside the 1.85 VSWR circle are 245MHz, 125MHz and 46MHz, respectively.