# Antenna-Duplexed Passive Beamforming Front-end for Joint Communication and Sensing

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***Abstract*—Wide scale deployment of wireless devices is making the spectrum a scarce resource. Joint communication and sensing (JC&S) and in-band full duplex (IBFD) communications provide opportunities of spectrum reuse. IBFD communication hardware requires high transmitter-to-receiver (TRx) isolation, making it shareable and reusable with mono-static continuous wave radar in JC&S context. On the other hand, design and development of beamforming phased arrays, required for communication coverage and radar spatial filtering, becomes challenging when a high TRx isolation assurance is required. This paper presents a solution in the form of antenna-duplexed passive beamformer usable for IBFD communication and mono-static continuous wave radars, mitigating two key challenges/requirements of JC&S hardware reuse in co-design approach - TRx isolation and beamforming capability. A beamformer using Butler matrix and a planar quasi-circulator are designed and optimized for X-band (centered at 10 GHz) providing up to 40 dB transmitter leakage suppression using primarily passive circuits.**

***Index Terms*—Antenna duplexing, Beamforming, Butler matrix, Circulator, Full duplex, Multiplexer, RF switch.**

## I. Introduction

In recent years, the interests towards joint communication and sensing (JC&S) systems have increased due to the clear benefits of such systems [1]. An immediate use case seems to be the coordination of radars. Similarly, for 6G applications, it can be the key enabler for context-aware communication systems and new application with spectrum reuse (e.g. radar-as-a-service). The spectrum reuse is needed to meet the increasing communication data capacity requirements while enabling a flexible allocation of resources. Hardware reuse is among the main benefits of a co-design approach between communication and radar systems while sharing front-ends and antennas as well as a joint physical and higher layers.

Antenna arrays are already used for gain boosting in communication systems and radars. In addition, phased antenna arrays with beamforming network (BFN) are ideal candidates for JC&S [2], especially for cmWave/mmWave applications. In addition to increasing the link margin, a switchable beam direction provides additional capacity and coverage for a communication system and spatial filtering for radar. BFNs can be classified into digital and analog w.r.t. the hardware implementation. Digital BFNs use a complete RF chain for each radiating element making possible multiple beams, shaped beams, and null steering at the cost of complex hardware and energy consumption [3]. Analog active BFNs need a dedicated variable phase shifter and amplifier for each antenna element while analog passive BFNs have a fixed phase shifter and attenuator for each antenna element. It is an economical and power-efficient way of beamforming at the cost of predefined fixed beam directions. Passive BFNs are implemented either with lens-based structures working on true-time-delay principles, e.g., Rotman lens [4] or through hybrid couplers and fixed phase shifters e.g., Blass, Nolen, and Butler matrices [5], [6]. Butler matrix has been a popular choice because of the implementation simplicity [7].

Simultaneous transmission and reception (STAR) has always been fundamental for mono-static continuous wave radars. However, as the spectrum is becoming a scarce resource, STAR is gaining attraction for in-band full duplex (IBFD) communication. IBFD communication can effectively double the channel throughput provided the transmitter (Tx) leakage towards the receiver (Rx) remains under the threshold. Various self-interference reduction approaches have been proposed using separate Tx and Rx antennas. They include pattern polarization, Tx null-steering towards Rx, antenna excitation and placement tuning [8]–[10], electromagnetic bandgap structures [11], and indented antennas [12]. However, using a single antenna for transmit and receive operation is preferable for the system form factor, especially in the case of MIMO, where several antennas are involved. Furthermore, a single antenna preserves the reciprocity of the wireless channel, which is required in several signal processing and encryption algorithms, e.g., channel reciprocity-based key generation in physical layer security [13]. Single antenna systems typically use a ferrite-based circulator with limited isolation, bulky size, expensive construction, and non-compatibility with semiconductor processes. On-chip active circulators have been proposed, but they are power-hungry [14], [15].

This paper presents an antenna-duplexed passive beamformer for X-band. Individually optimized building blocks are presented with a goal to study their integration options for high Tx-to-Rx isolation. Section II presents a Butler matrix with measurement results and a multiplexer for software-defined beam switching. A quasi-circulator design is presented in Section III with simulation results. The schemes of utilizing a passive beamformer for IBFD communication and mono-static radars are given along with simulation results in Section IV.

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## II. Passive beamformer design

A Butler matrix has N input ports connected to the output of a front-end using a multiplexer and N output ports, each exciting a radiating element of a phased array antenna. The Butler matrix produces a fixed phase difference between two consecutive output ports resulting in the tilt of the antenna beam. The choice of the input port controls the output phase or beam tilt. In this way, a $N \times N$ Butler matrix can produce N distinct beam directions. Applying signal to input ports 1,2,3 or 4 results in phase difference between two adjacent output ports of -45°, +135°, -135° or +45°, respectively.

### *A. Butler matrix design*

A planar $4 \times 4$ Butler matrix has been implemented for X-band applications. It comprises of quadrature hybrid couplers, planar microstrip cross-overs, and true-time delay transmission lines for phase compensation. A classical microstrip quadrature hybrid coupler has been used. Based on the quadrature coupler topology, a planar microstrip cross-over has been designed and optimized in EM simulation software for 10 GHz center frequency. The layout of the design is given in Figure 1 and simulation results are given in Figure 2.

Simulation results show a matched input for 1.5 GHz bandwidth at 10 GHz center frequency with a maximum of 0.6 dB insertion loss. Simulation shows a tight phase alignment for crossover, i.e., from port 1 to 3 and from port 2 to 4, which is essential for Butler matrix operation. The butler matrix layout accomplished by integrating quadrature coupler and microstrip cross-overs is given in Figure 3. The structure is optimized for 0.5 mm thick RO4003 substrate using EM simulation software (AWR Axiem) for matched insertion loss of all output ports at 10 GHz. Since a single input power is divided into four equal parts through distinct paths for each input port, optimizing one path affects the other. Because of the conventional quadrature coupler's limited serving bandwidth, the phase and division ratio changes rapidly with frequency for each power path. Hence, a narrow band response of the matrix is achieved. The simulated response of the Butler matrix is shown in Figure 4 with all combinations of power flow using Port 1 and Port 2 as inputs. The response of using Port 3 or Port 4 as input port is identical to using Port 2 or Port 1, respectively, due to the vertical symmetry of the structure and hence, not given in the figure. Simulated results show a maximum of 0.7 dB amplitude mismatch between any two output ports at the center frequency. The output phase differences between Port 5 and Port 6 and between Port 6 and Port 7 are plotted in Figure 5 respectively for excitation through Port 1 and Port 2. By vertical symmetry of the design, the phase difference between Ports 7 and 8 is determinable by the given information. Simulation results show a maximum phase error of 7.1° observed between output Port 6 and output Port 7 when the system is excited either through Port 1 or through Port 4.

A prototype of the Butler matrix is manufactured for laboratory measurements. Measurement results are taken using Keysight (PNA) Network Analyzer model N5224B, which has a frequency range from 10 MHz to 43.5 GHz. The calibration is done through Keysight N4693D electronic calibration kit. Rosenberger 32K243-40ML5 connectors are used for planar to coaxial conversion. The measured responses are plotted against the simulated responses on the same plots. A matched curve trend between simulated and measured responses is observed for all power paths. However, an additional insertion

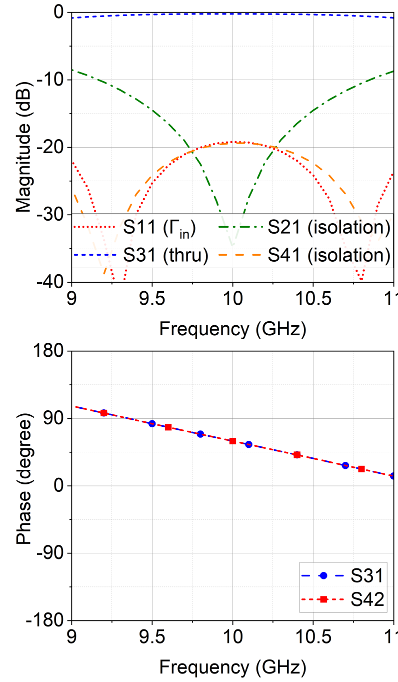



Fig. 2: Simulation results for microstrip cross over

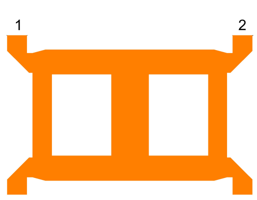



Fig. 1: Layout ($14 \times 9\, mm^2$) of microstrip cross over

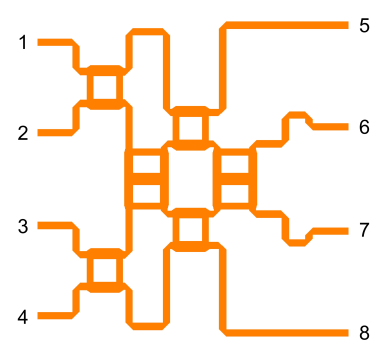
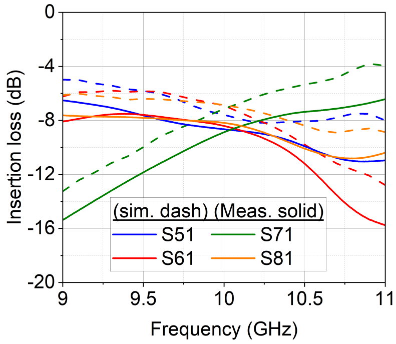
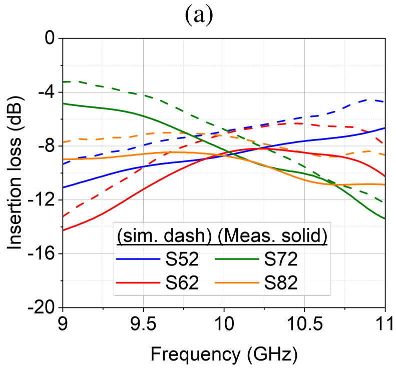



Fig. 3: Layout ($53 \times 54\, mm^2$) of the Butler matrix




(a)




(b)

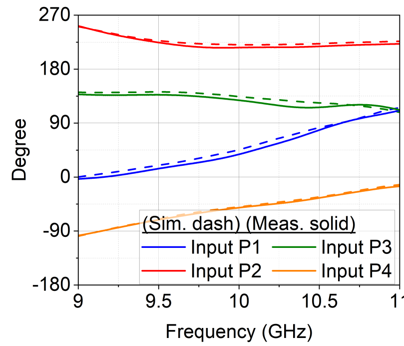
Fig. 4: Magnitude response of the Butler matrix when excited through (a) Port 1 and (b) Port 2

loss of 1.6 dB is noted at the center frequency. The loss is generated in planar to coaxial conversion, verified through a separate simulation. Measured input reflection coefficient at input Port 1 and Port 2 are plotted in Figure 6. A disagreement on Port 1 is observed due to connector influence. However, overall measured matching remains better than 10 dB.

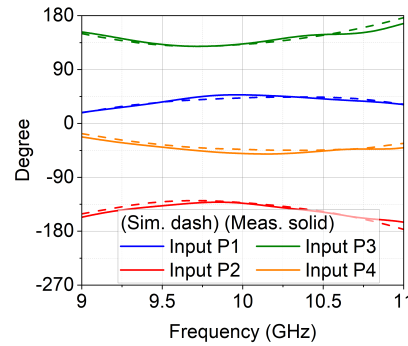
The simulated and measured results endorse the utilization of the designed structure for $4 \times 4$ passive beamforming. The Butler matrix is equipped with patch antennas for beam angle measurements in the next stage. A separate prototype has been manufactured for the measurements shown in Figure 7. The Butler matrix is mounted on a tripod stand with a graduated rotation angle against a second tripod carrying a reference horn antenna. Measurements are taken in a lab environment with Butler-array to reference-antenna distance of 1.6 meters by manual tripod rotation with Keysight network analyzer taking 10 frequency sweeps for each rotation angle. An average of 10 sweeps is considered for pattern plotting shown in Figure 8. Measured beam patterns show close agreement with the simulation results.

### *B. Development of input-multiplexing switch*

Since in the practical implementation of a Butler matrix, manual unplugging and plugging of the input port is not possible, a switching matrix is required. For this purpose, an SP4T RF switch module is developed using the ADRF5043 chipset. The output channel is selectable by a command line prompt on a computer using an on-module microcon-




(a)




(b)

Fig. 5: Phase response between (a) Port 5 and 6, and between (b) Port 6 and 7 of the Butler matrix

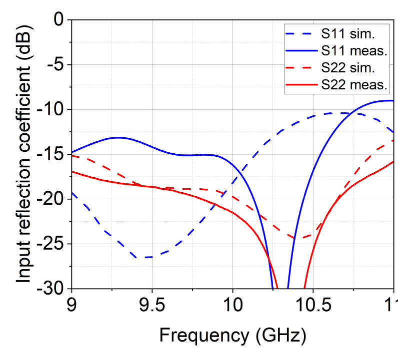



Fig. 6: Input return loss of the Butler matrix

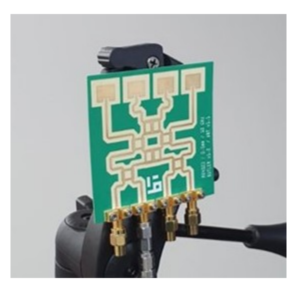


Fig. 7: Photograph of the developed Butler matrix

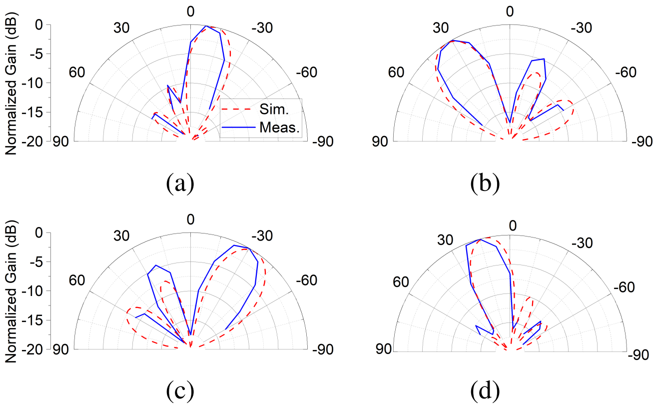



Fig. 8: Beam patterns generated by Butler matrix when excited by (a) Port 1, (b) Port 2, (c) Port 3 and (d) Port 4

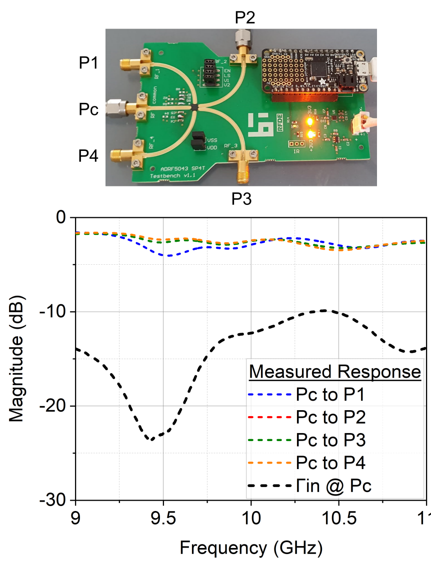



Fig. 9: Developed input-switching multiplexer module and the measured response

troller. The microcontroller can be programmed to work in an algorithm as well. A prototype photograph is shown in Figure 9 along with the measured input reflection coefficient and insertion loss from common port Pc towards each port.

A return loss of at least 10 dB is achieved from 9 to 11 GHz. However, it goes slightly below 10 dB on 10.4 GHz contrary to the datasheet providing values of 15 dB return loss worst case. Values achieved in a module can differ significantly from wafer-level measurements given in the datasheet due to soldering, long transmission lines, and connectors.

## III. Passive Antenna Duplexer: Quasi-Circulator

A circulator is required for duplexing because a switch can not support full duplex mode. A typical passive circulator is implemented by inserting a ferrite bead at the junction of three microstrips [16]. Alternative solutions are balanced circulators [18] and quasi-circulator using hybrid couplers [17]. Off-the-shelf circulators are generally available for sub-6 GHz bands

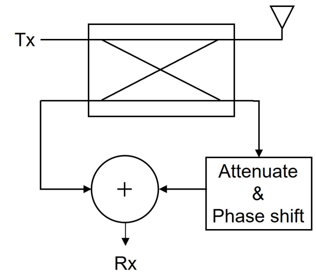



Fig. 10: Block diagram of the designed quasi-circulator

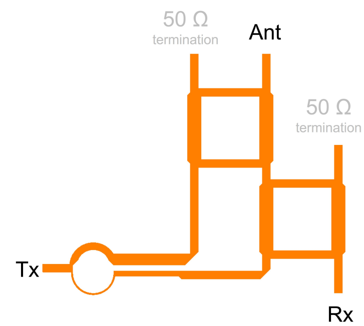



Fig. 11: Layout ($16 \times 20\,mm^2$) of the quasi-circulator (Ant= Antenna)

and offer limited isolation of 20-30 dB. Circulators in SMD configuration are scarce for X-band.

A hybrid coupler can serve as a circulator, and isolation can be increased by canceling the leakage through the out-of-phase addition of coupled signal, as shown in the block diagram in Figure 10. It can be performed either by an active circuit, or a combination of passive power combiners [17].

A quasi-circulator is designed for X-band using two quadrature couplers and one unequal Wilkinson power divider. The layout and simulation results are given in Figure 11 and 12, respectively.

When optimized for 10 GHz center frequency, the design shows a 10 dB input-matched response for both Tx and antenna ports, as indicated by Figure 12a. Insertion loss for Tx-to-antenna and antenna-to-Rx are 3 dB and 6 dB, respectively. Compared to a conventional hybrid coupler used as a circulator, Figure 12b shows that this design shows 10 dB additional isolation for the center frequency. However, while serving an extended bandwidth of 500 MHz, the conventional coupler offers isolation of 25 dB compared to this design offering 40 dB isolation.

## IV. Utilization of Passive Beamformer and Antenna-Duplexer in Mono-Static Radars and IBFD Communication

With a passive beamformer, the circulator can be integrated in two ways, either by installing a single circulator at the input of the switching matrix (case 1 in Figure 13) or one circulator at each input port of the beamformer and separate switching

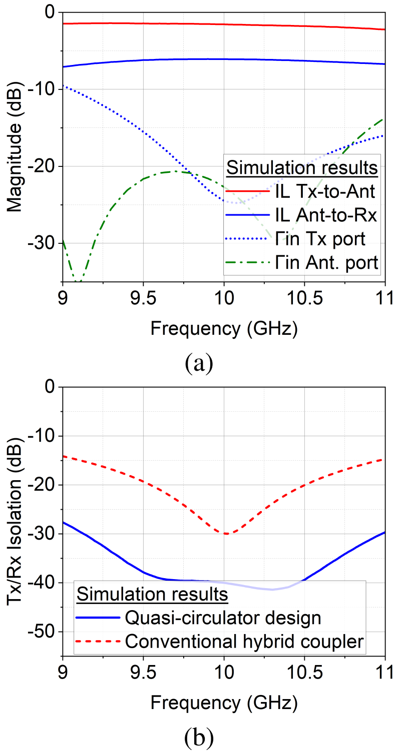



Fig. 12: (a) Input matching and insertion loss of the quasi-circulaton and (b) isolation comparison with a quadrature coupler (Ant= Antenna)

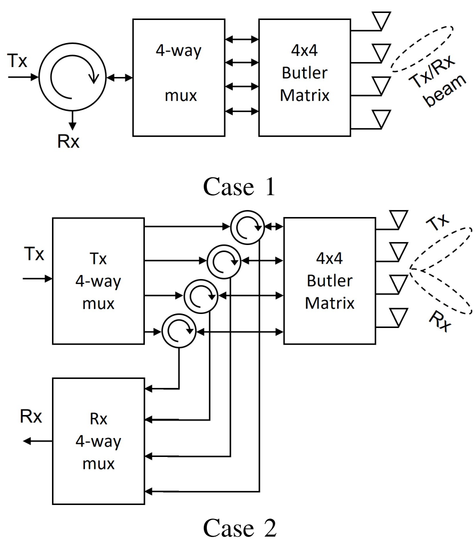



Fig. 13: Integration of Butler matrix with quasi-circulator (mux = multiplexer)

matrix for transmitter and receiver (case 2 in Figure 13). The former configuration provides simple circuitry while the latter provides the freedom of selecting transmit and receive beams independently, e.g., for a full-duplex base station serving multiple users.

In both cases, the circulator requires a highly matched load at its antenna port, whether a multiplexer switch (case 1) or

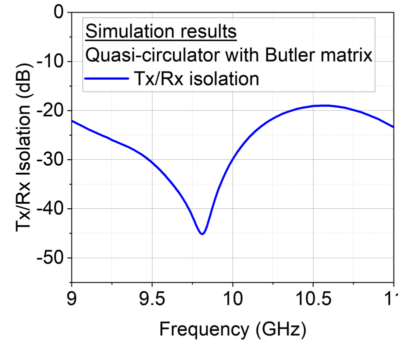



Fig. 14: Simulation results for the TRx isolation of the quasi-circulator connected to the Butler matrix

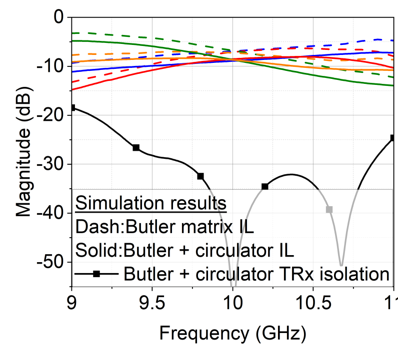



Fig. 15: Simulation results for Tx-to-antenna insertion loss and TRx isolation for the quasi-circulator integrated with Butler matrix through matching network

Butler matrix (case 2). It is valid for any type of circulator, quasi or ferrite based. Any mismatch on the antenna port reflects the Tx-generated signal towards the Rx port. An example case is simulated here for case 2, i.e., the Butler matrix as a load for the developed quasi-circulator. In this case, the achieved isolation with simulations is shown in Figure 14. Due to the mismatches, the TRx isolation degrades significantly. This response can be well understood when compared to the input reflection coefficient of the Butler matrix shown in Figure 6 (blue dash curve). Higher isolation is achieved where a better input match occurs. In contrast, isolation deteriorates at 10.5 GHz due to a poor input matching of the Butler matrix. However, the return loss of the Butler matrix was 10 dB at this frequency point. A 10 dB match which is generally considered a satisfactory input match, corresponds to the input reflection cofficient of 0.31 in linear scale. Hence reflecting 31% of the voltage wave. Hence, it is established that passive beamformers for full duplex communication must be designed with a very high level of input matching, which is challenging. An alternative is a matching network in between, which can provide a solution for narrow-band applications. The simulation results for the designed quasi-circulator and Butler matrix with a matching network in between are given in Figure 15.

With a matching network, the achieved isolation is 40 dB for the bandwidth of 200 MHz and 30 dB for 600 MHz when centered at 10 GHz. The total insertion loss of the assembly increases to 9 dB at the center frequency. A further high isolation level may be required if a power amplifier is needed at the transmitter to compensate for this insertion loss.

As a future work, the quasi-circulator will be fabricated and measured. As the input reflection coefficient curve of the input-multiplexing switch touches the -10 dB threshold, a matching network will be designed using EM simulation software by importing the measured response of the quasi-circulator and switch. An integrated design on a single substrate will be possible then. The designs are extendable to mmWave frequencies as well. At mmWave, a large bandwidth is desirable for high data rate communication and high-resolution radars. After verifying the concept at X-band, millimeter wave beamforming front-end will be designed as well.

## V. Conclusion

JC&S and IBFD communication both offer the potential to reuse the spectrum. However, beamforming antenna arrays impose a challenge for transmitter leakage towards the receiver impacting mono-static continuous wave radars and IBFD communications. This paper presents a Butler matrix design for passive beamforming in X-band along with simulation and measured results. In addition, an input-switching multiplexer is developed using SP4T RF switch. Since, separate beamformers and antenna arrays for transmitter and receiver increases the form factor significantly, an antenna duplexing quasi-circulator is designed and simulated, providing up to 40 dB of Tx/Rx isolation. Schemes for beamformer integration with a quasi-circulator are discussed, and simulation results are presented along with potential of this approach towards mmWave frequencies.

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