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A Dual-Mode Circulator Based on Folded SIW Technology for Full-Duplex Systems

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Abstract

In this paper, a twin-ferrite loaded folded SIW (FSIW) topology is proposed and explored to devise a methodology for the development and demonstration of a fully integrated compact dual-mode circulator. The device exhibits more than 700 MHz impedance matching bandwidth operating in a concurrent dual-mode at 5 GHz. The proposed scheme demonstrates a better than 60 dB isolation over 80 MHz bandwidth. Moreover, this device features an excellent tunability over entire operation bandwidth of interest while preserving 60 dB isolation over at least 80 MHz bandwidth. Considering these exceptional metrics, the proposed component presents an excellent candidate to be deployed in full-duplex (FD) systems.

Keywords — 5G, circulator, dual-mode, ferrite, full-duplex, nonreciprocity, multi-mode, SIW, TE10 mode, TE20 mode.

1. Introduction

Full-Duplex (FD) transceivers that transmit and receive signal simultaneously over the same band are a promising candidate for 6G and future wireless systems for their numerous exceptional advantages. However, enabling a true full-duplex operation is challenging because of their inherent self-interference (SI) signal resulted from transmitter coupling or leakage into receiver. Recently many researchers have realized and implemented FD systems through various techniques [1-3]; however, these techniques are either unfulfilling the requirements of a FD system in terms of bandwidth and isolation or are based on very complicated RF solutions with limited advantages that cannot compete with other existing half-duplex architectures in terms of power handling, noise, linearity, cost, efficiency, and so on.

In this paper, we propose and demonstrate an all passive fully integrated concurrent dual-mode circulator in FSIW technology. We will show that this special circulator is able to provide very high isolation over a broad communication bandwidth in contrast to conventional single mode circulators. More importantly, the isolation of the device can be easily tuned over the impedance bandwidth of the device for the desired performances.

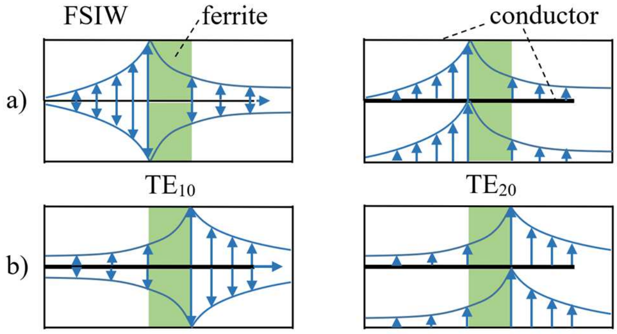


Figure 1. Electric field profile at the cross-section of a twin-ferrite loaded FSIW for TE_{10} and TE_{20} modes in (a) forward and (b) reverse direction of propagation.

2. Dual-Mode Circulator Based on FSIW Technology

An anti-symmetrically biased twin-ferrite-loaded substrate integrated waveguide (SIW) structure is a nonreciprocal medium. In [4-5], we have shown that under certain ferrite-biasing condition, it is possible to conduct the forward and reverse directed waves in two distinct channels, which is referred to as modal nonreciprocity [4]. In other words, in such a configuration, the forward directed wave propagates on the sides of the SIW; while the reverse directed wave propagates at the center of the SIW and between two ferrite slabs. Further, this structure can carry TE_{10} and TE_{20} modes concurrently within itself, provided that the SIW width is selected large enough to support the first two dominant modes [5]. On the other hand, the nonreciprocal field profile provides a basis to devise a dual-mode circulator [5], where additional ports are injected into the SIW from the side walls to interact with fields only in one direction.

Folded SIW (FSIW) has been known to inherit major properties of the SIW with a 50% size reduction topology, ideal for compact design. The anti-symmetrically biased twin-ferrite-loaded SIW topology can be casted into a folded structure. The electric field profile in the cross-section of the structure is illustrated in Figure. 1, when the ferrite is biased into modal nonreciprocal state. The field profiles are shown for both TE_{10} and TE_{20} modes and in both forward and reverse direction of propagation. Since dielectric constant of the ferrite is relatively large, the field is trapped and travels inside the ferrite like a dielectric waveguide. On the other hand, in this application, the ferrite is biased into negative effective permeability (μ_{eff}) region, which makes the ferrite cut-off. Therefore, the fields inside the ferrite will propagate at the interface of the ferrite. Because of this effect, in Figure. 1 the fields are concentrated at the interface of the ferrite slabs.

Further, due to the nonreciprocity of the ferrite, in the forward direction fields are accumulated on the left side of the structure, while in the reverse direction the fields are accumulated on the right side of the FSIW. Moreover, for the TE_{10} mode, the fields are similar to electric fields in the strip line. On the other hand, for the TE_{20} mode, the fields are similar to waveguide or microstrip, as if the center conductor is not present. This nonreciprocal behavior can be exploited to design a dual-mode circulator that operates simultaneously on both modes. For the TE_{10} mode, in the reverse direction, it is possible to nonreciprocally excite it using a stripline injected from the right side. Also, it is possible to excite the TE_{20} mode in the forward direction by connecting a microstrip to top and bottom conductors from the left side. However, since we don't need the latter port for our FD application in this design, we will not use it; theoretically the 3rd port of circulator is short-circuited for TE_{20} mode.

Therefore, the schematic of the proposed FSIW dual-mode circulator is shown in Figure. 2(a). In this design, two layers of the substrate with low permittivity of 2.94 are used to implement the FSIW. Ferrite slabs are embedded within each layer and on top of each other. A stripline from the right side of the structure is added to the FSIW to construct the circulator. To realize a nonreciprocal circulatory operation, a resonance and standing wave mechanism must be implemented in the junction. Therefore, a ring shape stripline is implemented here to create the resonance loop for the TE_{10} mode. It is possible to implement a similar resonator loop for the TE_{20} mode with microstrip line injected on the left side of the structure. However, in an FD application there is no need for that extra port. To achieve a high isolation in a FD transceiver, TE_{10} and TE_{20} modes are assigned separately to transmitter (Tx) and receiver (Rx) channels. Beside the inherent isolation that a circulator provides between adjacent ports, here Tx and Rx channels will experience a larger isolation due to the orthogonality of the modes. We assign the TE_{10} mode to Tx signals, and transmitter output is considered to get connected to port 3. The dual-mode port 2 is connected to two separate antennas or a dual-polarized antenna for radiation, depending on monostatic or biostatic configuration of antennas. The TE_{20} mode of the port 1 is connected to the Rx channel, which delivers the Rx signal sensed by the Rx antenna. The TE_{10} mode of port 1 is idle here, however in an FD system, it can be exploited as a tap for active SIC methods [2].

For measurement purposes, the proposed structure in Figure. 2(a) must be connected to planar TEM transmission lines. Hence, a concurrent transition from FSIW to stripline and microstrip lines were designed and optimized using CST Microwave Studio on both sides as shown in Figure. 2(b).

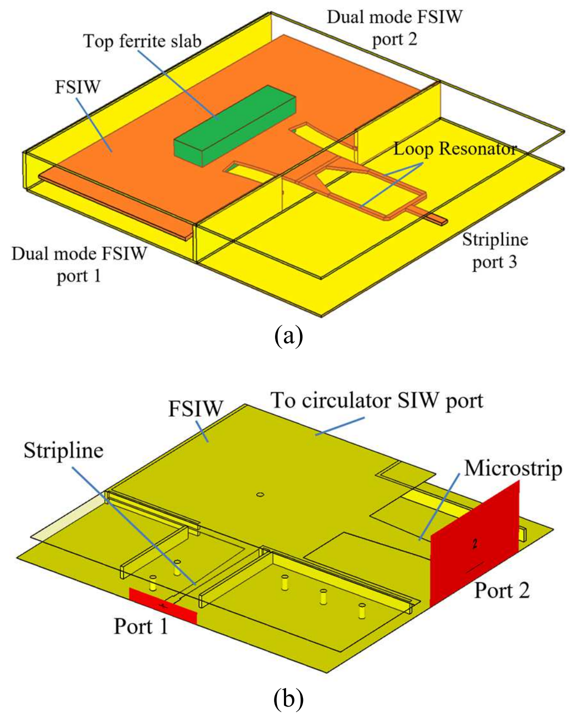
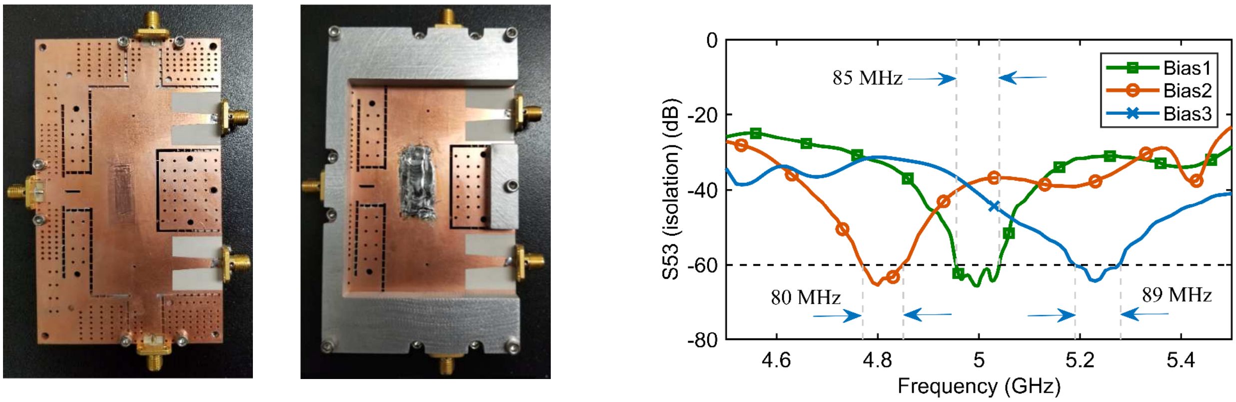


Figure 2. (a) Schematic of the FSIW dual-mode circulator. (b) Schematic of the proposed concurrent transitions from dual-mode SIW to stripline (exciting TE_{10}) and microstrip (exciting TE_{20}) TEM lines.

3. Fabrication and Measurement Results

The proposed FSIW dual-mode circulator is fabricated in PCB technology. The SIW is implemented on two Rogers 6002 substrates, glued to each other under pressure. The SIW via holes are implemented after gluing two layers using laser cutting through two layers and followed by a metallization process. After fabrication, ferrite slabs are embedded on each substrate within the slots that were cut in preparation stage of each layer. In addition, for electric continuity the ferrite slabs are covered by copper tapes and soldered to the SIW. The picture of the fabricated prototypes is shown in Figure. 3(a). A small portion of the second substrates on top of each stripline input is cut to facilitate connection of the connectors to the stripline ports. To provide the top ground for the stripline ports, a metallic base is fabricated and attached on top and bottom of the structure, which also provides a packaging for the device.

The S-parameter were measured using a Vector Network Analyzer. The device demonstrates a relatively wide bandwidth of about 730 MHz from 4.67 GHz to 5.4 GHz, with better than 10 dB return loss. Insertion loss is better than 0.8 and 1.7 dB at center frequency of 5 GHz for TE_{10} and TE_{20} modes, respectively, which is low considering the transitions and connector losses. For conciseness, only measurement result for the isolation is shown in this paper,



(a) (b)

Figure 3. (a) Fabricated prototype of FSIW dual-mode circulator with concurrent dual-mode transitions from SIW to stripline and microstrip transmission lines, for TE_{10} and TE_{20} mode excitation, respectively. (b) Measured isolation under three slightly different magnetic biases.

in Fig 3(b) for different magnetic biases. It should be mentioned that here port 3 denotes the stripline side-port assigned for Tx output, and port 5 denotes the microstrip line that excites TE_{20} mode in port 1 of the FSIW and is assigned for Rx input. It is observed using this technique we have achieved isolations better than 60 dB over at least 80 MHz bandwidth, which is suitable for FD applications in sub 6 GHz frequency range. Further and impressively, by a slight tuning of the magnetic bias of the ferrites, it is possible to tune the center frequency of the isolation all over the device bandwidth. As an example, this is shown in Figure. 3(b), by demonstrating a frequency tuning at center frequencies of 4.8 GHz and 5.24 GHz as well as 5 GHz.

4. Conclusion

In this work, we proposed and demonstrated a dual-mode circulator in FSIW technology, with ultra-high isolation which is better than 60 dB over at least 80 MHz bandwidth. In addition, the proposed device exhibits an excellent frequency tunability over whole operation bandwidth of more than 700 MHz.

The fact that such a high isolation over relative wide bandwidth for communication purposes is realized through an all-passive circuit is impressive. Because it results in several fascinating features necessary for enabling full-duplex systems. First of all, due to passiveness and exploiting an SIW topology, the device can handle very high-power signals. Second, due to passiveness again, the linearity and noise of the front-end are maximized and minimized, respectively. Third, the architecture is very simple in contrast to those complicated RF active circuit solutions. Forth, it does not consume any power to perform signal interference cancelation (SIC). Fifth, it is widely tunable. All these reasons demonstrate that this technique can be a game-changing solution for enabling full-duplex transceivers and should be subject to future research and development for any possible improvements.

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