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A 120GHz In-Band Full-Duplex PMF Transceiver with Tunable Electrical-Balance Duplexer in 40nm CMOS

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Abstract — A 120GHz in-band full-duplex PMF transceiver with tunable electrical-balance duplexer with on-chip antenna is implemented in a 40nm bulk CMOS technology. The self-interference (SI) cancellation is performed with a fully-differential transformer-based electrical-balance duplexer, resulting in a SI suppression of 30dB over a bandwidth of more than 14GHz. The insertion loss of the duplexer is less than 11dB from TX to fiber and less than 12dB from fiber to RX at a frequency of 120GHz. The balancing network impedance can tolerate load impedances from 45Ω to 93Ω and 38fF to 266fF at 120GHz. For in-band full-duplex operation, the maximum measured data rate is 6.2Gbps. The transceiver with integrated antenna occupies an area of $1.8\text{mm} \times 1.53\text{mm}$ and has a DC power consumption of 73mW in total.

Keywords — In-band full-duplex, Electrical-balance duplexer, Self-interference cancellation, Tunable balancing network, Polymer Microwave Fiber (PMF), 120GHz, Millimeter-wave, CMOS

I. INTRODUCTION

In recent years, research on Polymer Microwave Fiber (PMF) communication links in bulk CMOS [1]–[4] ([1], [2], [4]) has been increasingly popular. State-of-the-art simplex PMF communication links enable data rates up to 18Gbps and allow transmitting data over distances up to 15m [3]. To date, few papers have investigated the possibilities to create a bidirectional PMF link [4]. Bidirectional communication could be established by making use of several techniques exploiting orthogonality between up- and downlink:

- Channel Division Duplex (CDD) makes use of two different channels, one for the uplink and the other one for the downlink. The drawback is a low data rate for a given cable cross-section.
- Time Division Duplex (TDD) or half-duplex eliminates the use of two channels, but reduces the data rate since both links have to share the available time slots.
- Frequency Division Duplex (FDD) or full-duplex, is a well-known technique where two different frequency bands are assigned. This technique eliminates timing issues and there is no further need for fast switches. It has been demonstrated to be an excellent option for PMF duplex operation in previous research [4].
- Polarisation Division Duplex (PDD) has also been used for a PMF link in the work of [5] and [6], where the orthogonality of a horizontal and vertical polarization distinguishes the up- and downlink. PDD provides good isolation between TX and RX, but one of the major drawbacks is the more complex antenna structure to launch orthogonal waves.

Fig. 1. Architecture of the proposed transformer-based duplexer. The hybrid transformer is the core of the system and realizes the isolation between PA and LNA to suppress the SI signal.

This paper proposes an integrated In-Band Full-Duplex (IBFD) transceiver, where transmitter and receiver simultaneously use the same frequency band while communicating through the same channel. IBFD gains in terms of data throughput compared to traditional techniques such as FDD and TDD. The aim of this research is to design and implement an electrical-balance duplexer (EBD) transceiver at mm-Wave frequencies for a PMF communication link. The remainder of this work is organized as follows. Section II of this paper examines the EBD architecture in more detail. The measurement results are presented and discussed in Section III. Section IV presents the findings of the research and concludes the work.

II. IBFD TRANSCEIVER ARCHITECTURE

The EBD concept [7] is based on balancing the impedances observed at the antenna and the balancing network of the hybrid transformer as illustrated in fig. 1. This results in a suppressed signal transfer from transmitter to receiver, enabling bidirectional operation. A drawback of the EBD technique is the 3dB inherent loss in both transmitter and receiver paths, resulting in 6dB insertion loss for the entire link budget.

The proposed 120GHz IBFD transceiver is implemented as a fully-differential transformer-based EBD as illustrated in fig. 2. The hybrid transformer is the key building block and connects transmitter and receiver to the antenna in such a way that (1) the isolation between PA and LNA is sufficiently high, to reduce the SI leakage, and (2) the insertion loss from PA to fiber (S_{32}) or fiber to LNA (S_{13}) maintains as low as possible.

Fig. 2. Schematic overview of the fully-differential transformer-based EBD. Together with an on-chip antenna and the on-chip balancing network they form the major building blocks of the implemented transceiver.

Fig. 3. Die micrograph of the transceiver chip with outer dimensions of $1.8 \times 1.53 \text{ mm}^2$. The bowtie dipole antenna occupies an area of $0.44 \times 1 \text{ mm}^2$ and is fabricated in the aluminium top metal.

To achieve high data rates, the major challenge is to design the EBD with sufficient broadband isolation, which can only be achieved when the balancing network impedance matches the antenna impedance closely over the desired bandwidth. The exact impedance observed at the antenna feed depends on the composition of the entire coupling structure, including fiber and on-chip antenna. High isolation is therefore hard to achieve at mm-Wave frequencies, especially in combination with a low insertion loss. The hybrid transformer duplexer is designed in combination with an on-chip bowtie antenna, which has an inherently broadband behaviour and therefore facilitates the design of the balancing network. The entire duplexer including coupler is designed for a minimum isolation of 30dB and maximum insertion loss of only 12dB over a 10GHz bandwidth.

A. Hybrid Transformer

The layout of the hybrid transformer at 120GHz is depicted in fig. 4. The transformer is designed in the

Fig. 4. Detailed layout of the hybrid transformer. The inner and outer windings are designed in Metal 10, while the interconnect to the PA is constructed in Metal 9.

Fig. 5. Coupler implementation including a 2mm hollow PTFE fiber, a 3 layer Megtron6 PCB, a metal connector and a metal cage reflector. At 120GHz the entire coupler has a simulated loss of 7.1dB.

Fig. 6. Cross section of the 3 layer PCB. The bottom layer acts, in combination with the metalized buried vias, as a metal reflector cage to minimize the radiation losses into the Megtron6 substrate.

two topmost metal layers to minimize the resistive losses. The outer diameter is $124 \mu\text{m}$ and the traces are $3 \mu\text{m}$ wide. A fully-differential topology was chosen to facilitate the interconnect with the four surrounding circuits. A transformer-based matching network is used for impedance matching and allows to perform biasing for the PA and LNA.

B. Broadband Coupler

A bowtie antenna couples to the fundamental HE_{11} mode in the polymer fiber. The broadband behaviour of such antenna relaxes the specifications of the balancing network. The antenna is fabricated in the aluminium top metal as illustrated in fig. 3. To improve the coupling efficiency, a metal cage reflector is placed at the bottom

Fig. 7. Simulated S-parameters of the entire EBD including coupler and fiber. S_{32} and S_{13} have respectively 11dB and 12dB insertion loss, while the isolation S_{12} can be tuned over frequency.

of the Megtron6 PCB that reflects the EM wave back into the fiber as seen in fig. 5. The metal cage is constructed in a 3-layer PCB as highlighted in fig. 6. Metalized buried vias form the side walls to avoid that the EM waves radiate in the PCB substrate. The entire coupling structure from antenna feed to fiber is simulated in HFSS and has a insertion loss of 7.1dB with an impedance of $52-j17\Omega$ at 120GHz. The antenna measures 0.4mm by 1mm and the hybrid transformer has an outer diameter of $124\mu\text{m}$.

C. Balancing Network

To match the impedance of the broadband dipole antenna, the balancing network consists of a p+ poly resistor of 50Ω and two NMOS transistors as illustrated in fig. 2 and can be controlled using V_{ctrl1} and V_{ctrl2} . As a result, the balancing network impedance can tolerate load impedances between $92-j34\Omega$ and $45-j5\Omega$ corresponding to a resistance between 45Ω and 93Ω and a capacitance between 38fF and 266fF at 120GHz. Fig. 7 shows the simulation results of the isolation capability for different tuning settings. This results in a SI suppression of 30dB over a bandwidth of more than 14GHz. The duplexer insertion loss is less than 11dB from TX to fiber and less than 12dB from fiber to RX at a frequency of 120GHz and is nearly independent for the different settings of the balancing network.

D. Transmitter and Receiver Circuitry

The transmitter generates a two-tone FSK signal with 4GHz tone spacing at a carrier frequency of 120GHz and an RF power of -1.9dBm. The receiver demodulates the signal and drives a 50Ω load. At 6.2Gbps, the transmitter and receiver have a DC power consumption of respectively 13.56mW and 59.41mW with a supply voltage of 0.9V. A more detailed study on the transmitter and receiver circuitry can be found in [1].

III. MEASUREMENT RESULTS

The presented chip, of which a die micrograph is shown in fig. 3, is implemented in a 40nm bulk CMOS technology. The transmitter and receiver occupy an active area of respectively 0.025mm^2 and 0.43mm^2 .

The IBFD measurement setup is shown in fig. 8. To measure the isolation, a 120GHz two-tone FSK modulator launches a PRBS9 pattern with a power level of -6dBm in the fiber towards the transceiver, which receives and demodulates that signal while simultaneously transmitting a PRBS7 pattern. A Keysight 81250 parBERT verifies

Fig. 8. IBFD measurement setup. A BERT generates a PRBS9 pattern for the downlink and a PRBS7 pattern for the uplink to distinguish the SI from the signal in the analyzer. An oscilloscope captures the eye diagram.

Fig. 9. Measured bit error rate curve for for varying V_{ctrl1} while maintaining $V_{ctrl2} = 0.9\text{V}$.

the demodulated PRBS9 signal, resulting in a maximum measured data rate of 6.2 Gbps with a BER below 10^{-12} .

The eye diagrams, captured with a Keysight DSO-Z 634A 63GHz 160Gs oscilloscope, are presented in fig. 10 and fig. 11 for different bias settings of the balancing network. Fig. 10 illustrates the effect of tuning the balancing network on the SI signal. If only the PRBS7 uplink is active, the transceiver demodulates purely the SI signal that can be cancelled with a proper V_{ctrl1} setting of 0.55-0.7V (see region [B] in fig. 9).

Fig. 11 demonstrates the isolation performance of the on-chip EBD. With only the PRBS9 downlink active, the eye diagram is shown in fig. 11a resulting in SNR limited demodulation. If the PRBS7 uplink becomes active (see fig. 11b), the demodulation becomes signal-to-interference-plus-noise ratio (SINR) limited, since the SI signal disturbs the demodulation. After tuning the balancing network to region [B], the SI signal reduces significantly and the eye diagram is presented in fig. 11c.

Table I summarizes the performance of the proposed IBFD transceiver and compares the results against previously published work. The presented work is the first above 60GHz EBD transceiver with a real on-chip antenna load. The 14GHz SI bandwidth is the highest reported today, resulting in a data rate of 6.2Gbps.

IV. CONCLUSION

A 120GHz in-band full-duplex PMF transceiver with integrated antenna and tunable electrical-balance duplexer was proposed and implemented in a 40nm bulk CMOS technology. Simulation and measurement results were provided. The self-interference cancellation achieves 30dB over more than 14GHz bandwidth. For in-band full-duplex operation, the maximum measured data rate is 6.2Gbps using a 120GHz FSK modulation.

TABLE I
PERFORMANCE SUMMARY AND COMPARISON OF PREVIOUSLY PUBLISHED STATE-OF-THE-ART ELECTRICAL-BALANCE DUPLEXERS.

	Duplexer only					Duplexer with transceiver	
	TMTT'13 [8]	JSSC'13 [9]	ASSCC'15 [10]	TMTT'16 [11]	TMTT'16 [12]	JSSC'16 [6]	This work
Center Frequency [GHz]	2	2	2	2.1	30	60	120
SI Bandwidth [GHz]	0.5	0.2	0.1	0.229	1	1	14
SI Suppression [dB]	>40	>45	>45	>50	>45	>70	>30
Data Rate [Gbps]	-	-	-	-	-	>5	6.2
P _{TX} [mW]	-	-	-	-	-	206	13.56
P _{RX} [mW]	-	-	-	-	-	111	59.41
P _{canceller} [mW]	-	-	-	-	-	44	0
Cancellation Technique	EBD	EBD	EBD	EBD	EBD	Polarization + RF Cancellation	EBD
Load	broadband 50Ω	10-bit array switched resistor	broadband 50Ω	broadband 50Ω	Off-chip patch antenna	Off-chip patch antenna	On-chip bowtie dipole antenna
Topology	Fully differential	Single ended TX Differential RX	Single ended TX Differential RX	Single ended RX Differential TX	Single ended	Single ended	Fully differential
Technology	90nm CMOS	40nm CMOS	28nm CMOS	0.18μm SOI CMOS	0.25μm SiGe BiCMOS	45nm CMOS	40nm CMOS

Fig. 10. Measured eye diagrams for the interference signal only (a) at a data rate of 6.2Gbps with a BER below 10^{-12} . The balancing network suppresses the interference signal if the impedance is tuned correctly (b).

Fig. 11. Measured eye diagrams for simplex communication without interference signal (a), unbalanced (b) and balanced (c) IBFD communication at a data rate of 6.2Gbps with a BER below 10^{-12} .

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