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A Multi-Gigabit CPFSK Polymer Microwave Fiber Communication Link in 40 nm CMOS

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Abstract

This paper presents a multi-gigabit communication link over a polymer microwave fiber (PMF). A polymer fiber is a light-weight and low-loss channel at millimeter-wave (mm-Wave) frequencies. PMF is a promising, robust and low-cost technology to complement copper or optical links for high-speed applications with transmission distances up to several meters. The high carrier frequency of 120 GHz ensures low bending losses for small bending radii and features a large absolute bandwidth, which can be exploited to achieve high data rates with a simple modulation scheme. The used continuous-phase frequency shift keying (CPFSK) modulation results in a power efficient system at both the TX and the RX side. We report on 120 GHz 40 nm bulk CMOS TX and RX chips, the fiber and the coupling solution between the chips and the fiber. Data rates up to 12.7 Gbps over 1 meter, transmission lengths up to 7 meters at 2.5 Gbps and a link energy efficiency of 1.8 pJ/b/m for 4 meters and 7.4 Gbps are achieved for the complete communication link.

Index Terms

Plastic waveguide, Polymer microwave fiber (PMF), Multi-gigabit communication, CMOS integrated circuits, Millimeter-wave (mm-Wave) frequency range.

I. INTRODUCTION

Technology scaling has enabled RF-CMOS circuits that operate in the millimeter-wave (mm-Wave) frequency range (30 GHz - 300 GHz) where large bandwidths are available. These bandwidths can be exploited to increase the bit rate of data communication links. In literature, mm-Wave communication links operating at 100 GHz or higher exist [1]–[9], all of them using wireless transmission. The achieved communication distances are limited because of the large free-space path loss (FSPL) at these frequencies. This problem can be addressed by inserting very directive antennas or by using more stages in the PA and LNA. A cheaper and more power efficient approach, used in this paper, is to use a polymer microwave fiber (PMF) as the transmission channel for mm-Wave data communication. Such fiber can act as a low-loss channel for mm-Wave radio signals [1], [9]–[13], creating an alternative technology, complementary to optical and copper wireline. For link distances up to 10 meters, a PMF link appears to be a valuable alternative which can reach high data rates with a competitive link energy efficiency.

The paper is organized as follows. Section II describes the implemented system. Details about the channel and the coupling solutions are given in section III and section IV, respectively. The implementation of the transmitter is explained in section V and the implementation of the receiver in section VI. Finally, the measurements are shown in section VII.

II. SYSTEM DESCRIPTION

The proposed system is shown in Fig. 1. Three different technologies are combined in this system. The first of these is the PMF channel, which guides the modulated waveform from the transmitter to the receiver. This will be discussed in more detail in section III. The second technology component is the on-chip integrated antenna, which performs the coupling between the transceiver and the channel. The third part of the system is the 120 GHz continuous-phase frequency shift keying (CPFSK) transmitter and receiver, implemented in a 40 nm bulk CMOS technology. A clock signal triggers the transmitter and drives an on-chip PRBS9 generator. The output of the receiver is a demodulated analog baseband signal which is the received PRBS data. The high operating frequency of 120 GHz features a large absolute bandwidth and high data rates can easily be achieved, even with simple modulation schemes like CPFSK. The first

advantage of CPFSK modulation is that it exhibits a constant envelope waveform. As a result, non-linear amplifiers with lower power consumption can be used. In contrast to ASK modulation, the output power is constant and equal to its maximal value. Therefore, a VGA is not required in the receiver to compensate for loss variations in the channel. Another advantage of CPFSK is that it is possible to demodulate non-coherently. Compared to PSK modulation, the complexity of the demodulator and its power consumption will be lower. Finally, a CPFSK modulator is resistant against LO pulling [14].

The link budget analysis is given in Fig. 2. Similar to wireless links, only losses are considered in this analysis. The measured transmitted 120 GHz output power (P_{TX}) is -6 dBm. The coupling gain (G_{con}) between the chip and the PMF channel is -12 dB. The transmission channel loss (G_{ch}) is -2.5 dB/m. The link budget of a 1 m and a 10 m link is compared with that of a 10 cm wireless link. In the calculation of the wireless link an antenna gain of 4.5 dB is used. It can be seen that PMF technology increases the transmission distance by a factor of 100 compared to wireless transmission, for the same power and SNR at the receiver.

III. CHANNEL

Flexible polymer microwave fibers are available in a large variety of geometries, materials and dimensions. In this work, a hollow circular PTFE fiber with an outer diameter of 2 mm and an inner diameter of 1 mm is used. This fiber has a loss tangent of $4 \cdot 10^{-4}$, which is de-embedded from the measured loss per meter and this value is close to the one reported in [15].

A vector network analyzer (VNA) measurement of the loss per meter is given in Fig. 3a. The measured fibers are inserted into circular metal waveguides at both ends. The losses of the connection between the fiber, the metal waveguides and the extenders of the VNA are de-embedded with TOSM calibration. The fiber has a minimum loss around 105 GHz, but this is a measurement artifact due to the cut-off of the used metal waveguides. The loss of the fiber increases for increasing frequencies. Nevertheless, the reason to use a 120 GHz carrier frequency is the effect of frequency on bending losses. This effect can be observed in the measurements reported in Fig. 3b, which shows an additional loss of 1.5 dB for a 180° bend with a 25 mm radius. The bending losses decrease with increasing frequencies. The channel dispersion can be derived from the measured group delay shown in Fig. 3c [16] and is less than 100 ps for a

20 GHz bandwidth. Simulation results in Fig. 4 show the electric field in a bent fiber for different operating frequencies. At 160 GHz, the wave stays confined in the fiber (fig. 4c). This is a strong argument to go to higher operating frequencies when using PMF technology. Nevertheless, $f_{\max}$ (270 GHz) limits the transistor gain at higher frequencies. Balancing transistor gain, channel losses and bending losses, an operating frequency of 120 GHz is chosen for this design.

IV. COUPLERS

The coupling of the signal from chip to fiber is realized with a collinear broadside array antenna. A schematic view of the implementation is depicted in Fig. 5. In this work, both transmitter and receiver chip are packaged on a standard PCB substrate by making use of flip-chip technology to avoid bondwires altogether. Major disadvantages of coupling structures with bondwire antennas are that these fragile antennas are easily damaged when touched by the fiber and that they are very sensitive to process variation. The approach in this paper addresses these drawbacks, thus eliminating one source of variability and simplifying the connector alignment. The alignment issue is solved by introducing a metal connector on top of the chip that positions the fiber. The robustness of the connector solution is verified by measuring the loss due to misalignment of the fiber and the antenna. Fig. 6 gives the misalignment loss for both a displacement in the H-plane and in the E-plane. This means that no accurate alignment is necessary when attaching the metal connector and the fiber to the chip and that the couplers are robust against vibrations. Measurement results show a loss of 12 dB for the collinear broadside array coupler. The measurement setup contains a transmitter with fiber and a calibrated PM5 power meter.

V. CPFSK TRANSMITTER

The block diagram of the CPFSK transmitter is shown in Fig. 7. A differential clock is brought on-chip and drives a PRBS9 generator, which directly changes the oscillation frequency of the digitally controlled oscillator (DCO), see Fig. 8. Combining the 120 GHz DCO and the modulation functionality in one building block results in a low-power transmitter architecture. An amplifier buffers the 120 GHz output signal which is matched to the antenna.

The proposed switched capacitor (SC) implementation is given in Fig. 9. Compared to the conventional implementation of [17], [18], two small switches turn on simultaneously with the main switch. As a consequence, the injected channel charge, caused by turning on the main switch, is removed quickly. Although the closing operation of the switch remains unchanged, this implementation enables fast switching because the falling edge of the capacitance is not affected that much by the charge injection. The advantages are that no additional clock signals are required and the additional transistors are small and do not reduce the tuning range.

The DCO consumes 9.3 mA from a 0.7 V supply. The center frequency of the modulation can be tuned by two SCs which give an offset of approximately 2 GHz each. The third SC causes frequency jumps of approximately 4 GHz and is used for the modulation. The choice for a 4 GHz tone spacing is based on the trade-off between bandwidth and output voltage swing of the demodulator. A transient simulation of the DCO is given in Fig. 10. The output amplifier, with a power consumption of 4.5 mW, is implemented with a neutralized differential pair and a matching network to the antenna as depicted in Fig. 11. A more detailed derivation of this technique is given by [19].

Fig. 12 shows a simulation of the maximum available small-signal gain and the effective large-signal gain of the differential pair and the large-signal gain of the whole amplifier including the transmission lines and transformer. Due to the large input voltage swing coming from the oscillator, the gain drops from 7.8 dB to 5.6 dB. The output of the differential pair is matched to the antenna with two transmission lines and a transformer. The matching loss at the output of the differential pair is only 0.1 dB and the loss of the matching network itself is 1.3 dB. These results in a gain of 4.2 dB for the total amplifier. The simulated output power of the transmitter is -1 dBm and varies only 0.6 dBm over the whole tuning range of the DCO.

VI. CPFSK RECEIVER

The CPFSK receiver topology is depicted in Fig. 13. The LNA amplifies the incoming signal to the required level for the demodulator. Because it is not feasible to implement a filter that can detect the different input tones, due to the extremely high Q-factor that would be required for such a filter, an architecture with splitter, phase shifter and mixer is proposed. The function of the phase shifter is to transfer the frequency information in the input signal into phase

information which can be detected by the mixer. Both inputs of the mixer, V_1 and V_3 , have the same frequency, and as a consequence, the output of the mixer is a baseband signal for which the amplitude is dependent on the instantaneous phase difference between the inputs. A measurement buffer further amplifies the signal to drive the $50\ \Omega$ measurement equipment.

The implementation of the LNA is shown in Fig. 14. Every single stage consists of a neutralized differential pair. The cross-coupled capacitors are implemented as inactive NMOS devices. To prevent the accumulation of trapped charges in the inactive device channel during fabrication, the source is connected to ground with a $17\text{ k}\Omega$ resistor [20]. The gain of the differential amplifier, with a transistor width of $16\ \mu\text{m}$, is 7.6 dB and the loss in the matching network is 1.96 dB, resulting in 5.64 dB for each of the 5 stages. An additional loss of 1.4 dB in the input matching network, results in a total gain of 26.8 dB at a center frequency of 124 GHz. The bandwidth is 13.2 GHz, the noise figure 7 dB and the power consumption 41.5 mW.

The first building block of the demodulator is a power splitter. The splitter is implemented similar to an LNA stage, but it has two outputs. One output is connected to the mixer and the other one to the phase shifter. Both loads consist of a neutralized differential pair with the same transistor sizes so that the load impedances are very similar. The layout of the splitter is shown in Fig. 15. The primary winding of the transformer consists of two sub-coils in metal 9. The 2 secondary windings are implemented in metal 10. The power gain of the splitter, including differential pair with matching network, is 2.4 dB.

The phase shifter is the second building block. Its function is to convert frequency modulation into phase modulation. A tuned amplifier, consisting of a neutralized differential pair and a matching network, exhibits a frequency dependent phase shift with broadband behavior. Fig. 16 gives the phase difference between the output and the input of the phase shifter as function of frequency. The maximum conversion gain is $3.2^\circ/\text{GHz}$. The DC power consumption is 1.3 mW.

The last component of the demodulator is the mixer. The circuit is implemented as a Gilbert-cell mixer. The mixer converts a phase difference into a differential baseband voltage signal. The conversion is shown in Fig. 17. The graph shows a steep curve in a large range of input phase differences. The mixer gives a maximum conversion gain of $4.3\text{ mV}/^\circ$ and the power consumption is 2.8 mW.

VII. MEASUREMENTS

The CPFSK transmitter and receiver chips are implemented in a 40 nm bulk CMOS technology. The die micrographs are given in Fig. 18. The active area of the transmitter takes only 0.03 mm^2 , but the on-chip antenna takes 0.81 mm^2 . The active area in the receiver is 0.45 mm^2 . A larger area was needed because of the five-stage LNA. The remainder of the area is used for decouple capacitors and the measurement buffer.

The measurement setup of the entire link is as follows. The fiber, discussed in section III, is placed between transmitter and receiver. The analog baseband output of the CPFSK receiver is connected to an oscilloscope to visualize the eye diagrams or to a BERT which recovers the data and compares it against the known sequence generated in the transmitter. In these measurements, no decision feedback equalization or error correction is used.

Distances up to seven meters are measured for a data rate of 2.5 Gbps. The highest data rate is 12.7 Gbps for a one meter link. The optimum distance times data rate product is achieved for a distance of four meters and a data rate of 7.4 Gbps. With a power consumption of 11 mW in the transmitter and 41 mW in the receiver this gives a link energy efficiency of 1.8 pJ/b/m for the complete link. Fig. 19 shows the measured eye diagrams and a bathtub curve of the analog baseband output of the receiver. The results are compared against previous published PMF communication links in table I.

VIII. CONCLUSION

This paper presented a PMF communication link. The polymer fiber is a low-weight transmission channel which has low losses at mm-Wave frequencies. The proposed link uses a CPFSK modulation on a 120 GHz carrier. The system is power efficient due to the constant-envelope CPFSK modulation and the non-coherent demodulation. The high-frequency carrier gives the advantage of low bending losses in the fiber. A robust connector between a flip-chip die and the fiber is presented. Data rates up to 12.7 Gbps for a one-meter link and distance up to seven meters for a 2.5 Gbps data rate are presented. These results indicate that PMF is promising where optical links are too expensive to deploy or don't have enough mechanical robustness and copper links are too sensitive for EMI.

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TABLE I

Reference	ISSCC'11 [11]	JSSC'11 [12]	MWCL'13 [13]	This work
Technology	40 nm CMOS	40 nm CMOS	65 nm CMOS	40 nm CMOS
Carrier frequency [GHz]	80	57	60	120
Material waveguide	PS	PS	PTFE	PTFE
Shape waveguide	Filled, rectangular	Filled, rectangular	Hollow, circular	Hollow, circular
Dimensions waveguide [mm]	1.1 x 1.8	1.1 x 1.8	ø3.2 x ø2.6	ø2 x ø1
Modulation scheme	ASK	ASK	ASK	CPFSK
Transmission distance [m]	0.12 1	0.1 1	2 7.6	1 4 7
Data rate [Gbps]	12.5 4.3	15 10	6 3.3	12.7 7.4 2.5
Rate x Distance [Gbps x m]	1.5 4.3	1.5 10	12 25.1	12.7 29.6 17.5
Link energy efficiency [pJ/b/m]	48 16.7	47.3 7.1	2.3 1.1	4.8 1.8 4.1
Area [mm ²]	0.06(TX) + 0.14(RX)	0.07(TX) + 0.14(RX)	0.06(TX) + 0.08(RX)	0.03(TX) + 0.45(RX)
Antenna	Quasi-Yagi on PCB	Quasi-Yagi on PCB	Off-chip dipole	On-chip collinear broadside array