3-5 V, 3-3.8 MHz OOK Modulator with a-IGZO TFTs for Flexible Wireless Transmitter

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***Abstract* This paper presents an On-Off-Keying (OOK) modulator for a flexible and wearable wireless transmitter implemented in an amorphous-Indium-Gallium-Zinc-Oxide (a-IGZO) TFT technology. The circuit consists of a three-stage ring oscillator for the carrier and an output driver with an OOK modulation switch, realized with just five transistors. In order to maximize the operation frequency, we use 2 µm-long nMOS transistors in the circuit design. The proposed OOK modulator is fabricated on a polyimide flexible substrate, and characterized with 3-to-5 V supply voltages and an output load capacitance of 15 pF. The circuit operates from the lowest supply voltage of 3 V, while the highest measured oscillation frequency is 3.76 MHz at 5 V V_{DD}. Although the schematic is simple and straight forward, the equivalent modulation depth ranges from 61.3 % to 78.2 %, which can be detected with an existing AM/OOK receiver in the same technology. The power consumptions for 3 V and 5 V supply voltages are 2.15 mW and 6.77 mW, respectively.**

***Index Terms* — OOK, a-IGZO, flexible electronics, oscillator.**

I. Introduction

There is a practical gap between conventional rigid electronics and bendable daily-life items such as paper, tapes, human body and textiles. This gap can be bridged by thin film, and large area electronics, which offers bendability, light weight, ultra-thin dimensions, transparency, stretchability, suitability for large areas, low costs among several other attractive features [1].

With the increase of the operation frequency of flexible electronics, wireless communication is becoming one of the promising applications and is being widely studied [2-8]. However, most of the previous works are proximity links such as RFID/NFC tags [2, 4-6] and power transmission [3], whose carrier – typically 13.56 MHz – is fed by either a base station or a data reader.

In contrast to existing flexible RFIDs, we aim at realizing a stand-alone transmitter, which can send arbitrary data over a distance longer than that of RFIDs to extend the application of the flexible electronics. The target transmitter includes oscillators and sensors for flexible and wearable electronics as shown in Fig. 1(a). In this context, we present an On-Off-Keying (OOK) modulator implemented in an amorphous-Indium-Gallium-Zinc-Oxide (a-IGZO) TFT technology to demonstrate the feasibility of a flexible and wearable wireless transmitter.

II. Circuit Design

Figure 1(b) shows a simplified block diagram of the target wireless transmitter including an OOK modulator, sensors, and a comparator. Since we assume that a two-to-four-time frequency multiplier in the same technology will be employed, the target frequency of the oscillator in the OOK modulator is around 3.39 MHz to achieve the Industry Science Medical (ISM) band of 6.78/13.56 MHz. By considering the tradeoff between the operation speed and the process yield, we choose 2 µm-long nMOS transistors maximizing the speed and a three-stage ring oscillator minimizing the number of transistors. The schematic of the proposed OOK modulator and the simulation configuration are shown in Fig. 2. The circuit consists of a three-stage ring oscillator for the carrier (M1-M3) and an output driver (M4) with an OOK modulation switch (M5). Since the circuit employs passive resistors instead of active loads, the total number of transistors is only five.

The transistor dimensions and resistances are chosen with

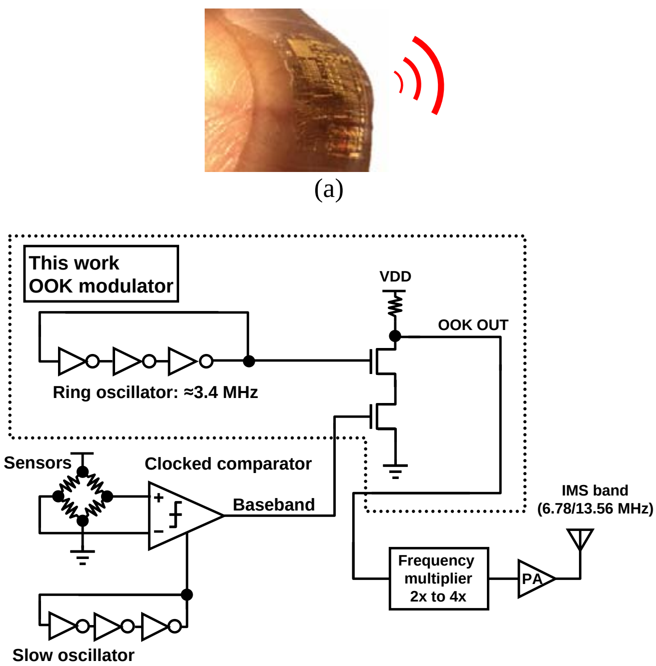


Fig. 1. An example of a flexible wearable transmitter. (a) An image of the target application. (b) A simplified block diagram of the wireless transmitter.

 DOI of this work: 10.1109/COMCAS.2017.8244748

circuit simulations. In the simulations, our device models are based on [9, 10] for our a-IGZO technology [11]. In order to predict the threshold voltage (V_{TH}) variation, we add a parameter, "delvto" that modifies V_{TH}. In the simulations, V_{TH} is varied from -0.15 V (fast) to + 0.15 V (slow).

Figure 3 (a) shows the simulated waveforms with the typical V_{TH} transistors and 3 V V_{DD}. The simulated carrier frequency is 3.39 MHz, which is a quarter 13.56 MHz. The output amplitudes of on-state, "V_{ON}" and off-state, "V_{OFF}" are 330 mV and 59 mV, respectively. Figure 3 (b) summarizes the simulation results from the all combination of delvto(-0.15 V, 0 V, +0.15 V) and V_{DD} (3 V, 4 V, 5 V). Even in the slowest condition, namely slow transistors (delvto=+0.15 V) and 3 V V_{DD}, the carrier frequency exceeds 3 MHz. In the fastest condition (delvto=-0.15 V, V_{DD}=5 V), the simulated carrier frequency achieves 3.79 MHz. For this circuit, the carrier frequency can be tuned by adjusting V_{DD}. However, we are developing a varactor compatible to our a-IGZO TFT technology. By using the varactor, we can realize a Digitally Controlled Oscillator (DCO) based on this ring-oscillator.

III. Experimental Results and Discussion

A. Experimental Results

The proposed OOK modulator is fabricated on a 50 µm-thick polyimide substrate with the non-self-aligned a-IGZO TFT technology [11]. For the high-speed circuit design, a thick metal layer "M3", which reduces both parasitic capacitance and resistance of the interconnections [12], is added as shown in Fig. 4. A chip photograph of the fabricated circuit is shown in Fig. 5, and its area is 1.5 x 3.0 mm^2.

The circuit is characterized with 3-to-5 V supply voltages and an output load capacitance of 15 pF as shown in Fig. 2. The circuit operates with the supply voltage of 3 V as shown in Fig. 6(a) The measured carrier frequency is 3.04 MHz, which is slightly higher than that of the slowest (delvto=+0.15 V, V_{DD}=3 V) simulation result. On the other hand, the output amplitude V_{ON} of 25 mV is much smaller than that of the simulation result, and the modulation depth is 61.3 %. This may come from a mismatch of the driving capability of the transistor and its load resistance. The output amplitude can be increased by adjusting the load resistance.

Figure 6(b) shows the measured waveforms with 5 V V_{DD}. The oscillation frequency is 3.76 MHz. The output amplitude is much improved compared with the result at 3 V V_{DD}, and the modulation depth achieves 78.2 %. Although the schematic of the presented OOK modulator is simple and straight forward, the equivalent modulation depth ranges from 61.3 to 78.2 %, which can be detected by our flexible AM/OOK receiver presented in [8]. The power consumptions with 3 V and 5 V V_{DD} are 2.15 mW and 6.77 mW, respectively. The measured performances are summarized in Fig. 6(c). The results show good consistency from 3-to-5 V V_{DD}.

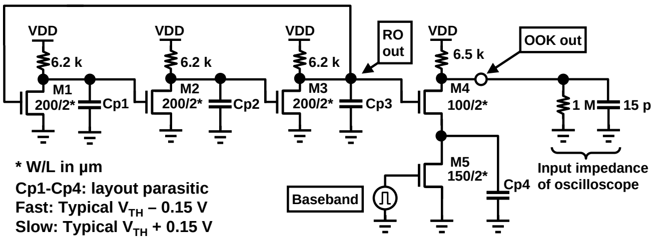
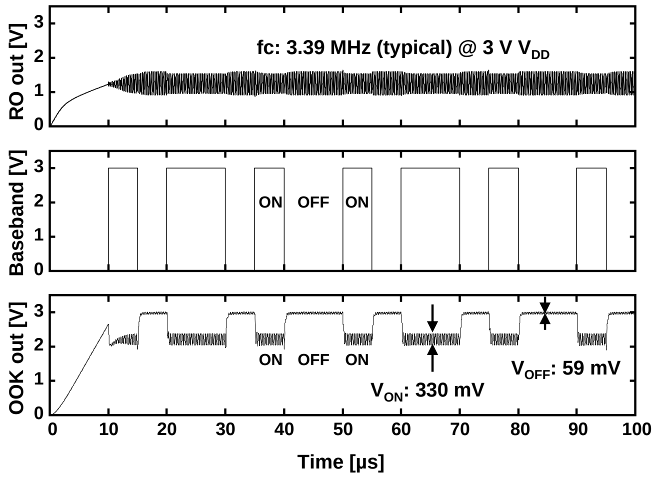


Fig. 2. The schematic of the proposed OOK modulator and the simulation/measurement configuration.



(a)

VDD		3 V	4 V	5 V
Carrier frequency	Fast (delvto=-0.15 V)	3.58 MHz	3.74 MHz	3.79 MHz
	Typical (delvto=0 V)	3.39 MHz	3.48 MHz	3.66 MHz
	Slow (delvto=+0.15 V)	3.02 MHz	3.28 MHz	3.55 MHz
Equivalent modulation depth (V_{ON}-V_{OFF}) / (V_{ON}+V_{OFF}) x 100		63-72 %	63-69 %	60-89 %

(b)

Fig. 3. Simulation results of the OOK modulator. (a) Simulated waveforms with typical V_{TH} (delvto=0) transistors and 3 V V_{DD}. (b) Summary of the simulation results.

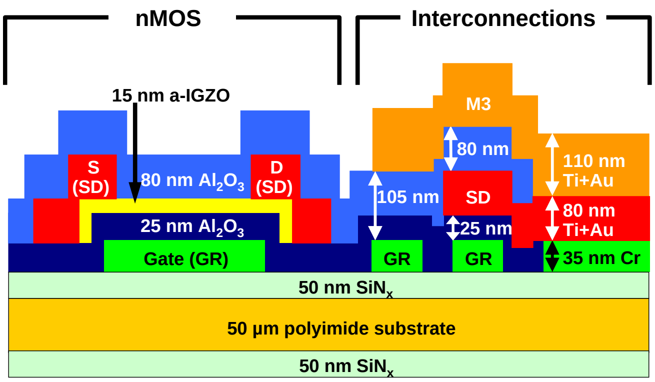


Fig. 4. Device structure of the flexible a-IGZO TFT. The device and interconnection with three metal layers ("GR", "SD", "M3") are formed on a 50 µm-thick polyimide substrate.

Figure 7 compares the measured- and simulated carrier frequency against supply voltage. The measurement results agree with the simulation results. By introducing the non-physical parameter "delvto" to TFT simulation models, it is possible to carry out fast-, typical-, and slow-simulations, thus enabling better predictions in the circuit design phase.

B. Comparison with the State-of-the-Art

Table I shows a comparison of flexible electronics for wireless application. Most of the previous works are proximity links such as RFID/NFC tags [2, 4-6] and wireless power transmission [3], whose carrier – typically 13.56 MHz – is fed by either a base station or a data reader. In contrast to them, we are aiming at a stand-alone wireless transmitter that enables sending arbitrary data over a distance up to several meters by using low-voltage, flexible TFTs.

In terms of low voltage operation, the circuit in [2] has a ring oscillator implemented with organic TFT, and can operate at 2 V, which is the lowest reported so far. However, the operation speed is slower than 10 Hz. On the other hand, a DCO generating 19.8 MHz sinusoidal wave and implemented with ZnO was recently reported [13]. However, the device is formed on a rigid glass substrate and requires 15 V V_{DD}. The circuit is therefore not suitable to flexible and wearable electronics. Within this context, the proposed circuit achieves the highest operation frequencies of 3.04-to-3.76 MHz at 3-to-5 V V_{DD} as an OOK modulator with a built-in oscillator in a flexible a-IGZO TFT technology.

IV. Conclusion

This paper presents an On-Off-Keying (OOK) modulator for a flexible and wearable wireless transmitter implemented in an a-IGZO TFT technology. The proposed circuit is fabricated on a polyimide flexible substrate, and characterized with 3 to 5 V supply voltages and an output load capacitance of 15 pF. The circuit operates from the lowest supply voltage of 3 V, and the measured oscillation frequency is 3.76 MHz at 5 V V_{DD}, which is the highest as an OOK modulator with a built-in oscillator in a flexible a-IGZO TFT technology. By adding a two-to-four-times frequency multiplier to the output of the proposed modulator,

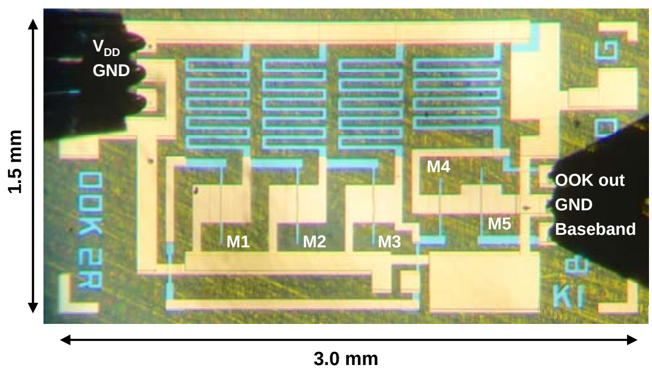
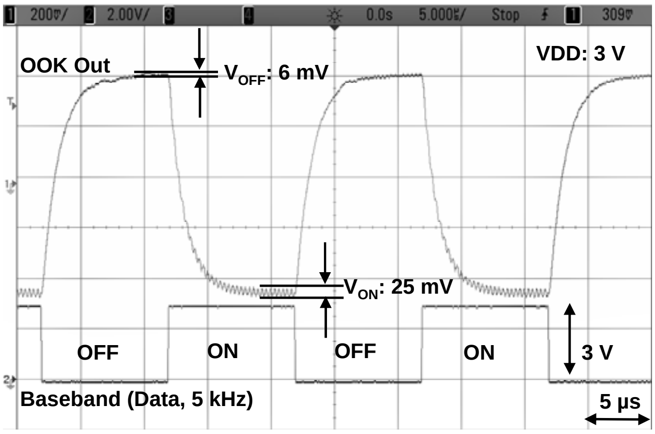
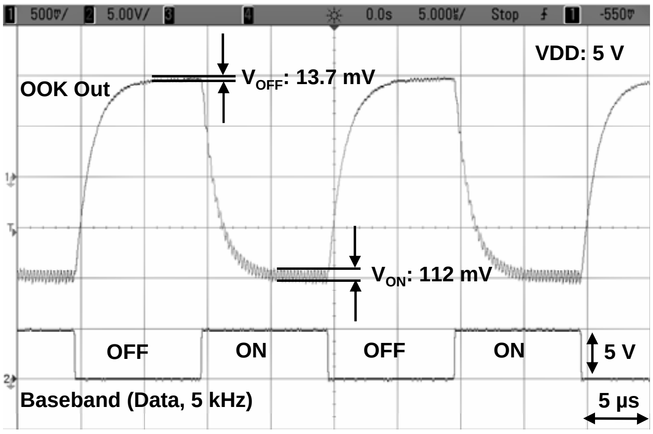


Fig. 5. Chip photograph of the fabricated OOK modulator implemented with 2 µm-long nMOS TFTs.



(a) Measured waveforms with 3 V V_{DD}



(b) Measured waveforms with 5 V V_{DD}

VDD	3 V	4 V	5 V
Carrier frequency	3.04 MHz	3.44 MHz	3.76 MHz
Equivalent modulation depth (V_{ON}-V_{OFF}) / (V_{ON}+V_{OFF}) x 100	61.3 %	74.7 %	78.2 %
Power consumption	2.15 mW	4.08 mW	6.77 mW

(c) Summary of the measured performances

Fig. 6. Measurement results of the OOK modulator. (A) Measured waveforms with 3 V V_{DD}. (b) Measured waveforms with 5 V V_{DD}. (c) Summary of the key measured performances.

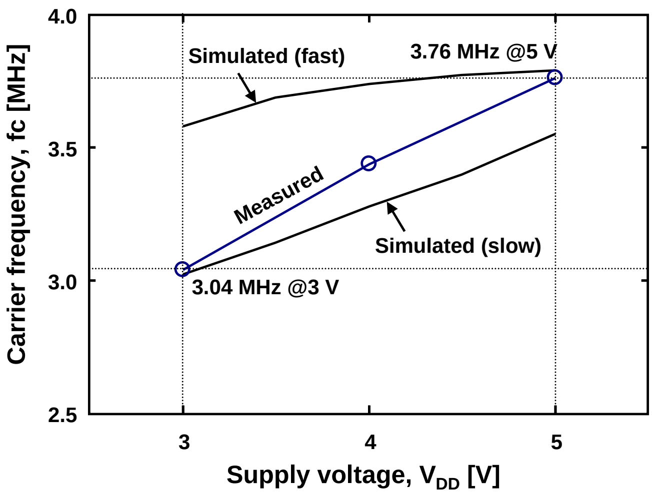


Fig. 7. Comparison of the measured- and simulated-carrier frequency vs. supply voltage.

TABLE I

COMPARISON OF FLEXIBLE ELECTRONICS FOR WIRELESS APPLICATION

	Ref [2] 2006	Ref [3] 2007	Ref [4] 2014	Ref [5] 2014	Ref [6] 2015	Ref [7] 2017	Ref [8] 2015	This work
Technology	OFET (pmos)	OFET (pmos)	OFET (p) Metal oxide (n)	OFET (pmos)	OFET (CMOS)	IGZO (nmos)	a-IGZO (nmos)	a-IGZO (nmos)
V_{DD}	100 V	40 V	7.5 V	2 V	24 V	3 V	5 V	3-5 V
Carrier Freq.	13.56 MHz (external)	13.56 MHz (external)	13.56 MHz (external)	13.56 MHz (external)	13.56 MHz (external)	13.56 MHz (external)	1-20 MHz (external)	3-3.8 MHz
Data rate/ BW	1 kbps	N/A	20.6 kbps (at 10 V)	3 Hz	50 bps	105.9 kbps	0.4-10 kHz	≈10 kbps
Coupling	Capacitive	Inductive	Inductive	Inductive	Inductive	Inductive	Inductive/ radio wave	Inductive/ radio wave
Application	RFID tag	Wireless power transmission	RFID tag	Medical sensor	RFID tag	RFID/NFC tags	AM/OOK receiver	OOK transmitter
Remarks	First RFID tag with OFET	200 mW η=50 %	Code gen. can operate at 3.75 V	Back scattering	With envelope detector	Vbias = 6 V CLK=847.5 kHz	First AM receiver with a-IGZO	Internal oscillator for carrier

the carrier frequency can reach the ISM band of 6.78/13.56 MHz. The equivalent modulation depth ranges from 61.3 % to 78.2 %, which can be detected by our existing flexible AM/OOK receiver in [8]. This demonstrated the feasibility of a flexible and wearable wireless transmitter.

ACKNOWLEDGEMENT

This work was supported in part by the Organic/Polymer Path of Center for Advancing Electronics Dresden, in part by the German Research Foundation (DFG) under projects Low-Voltage High-Frequency Vertical Organic Transistors (HFOE, EL 506/13-1), WISDOM, and Coordination Funds of SPP 1796, and in part by SNF/DFG DACH FFlexCom project: WISDOM, SNF grant number 160347.

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