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Linear Incremental Displacement Measurement System with Microtransformers

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Abstract: The paper discusses an inductive microsensor system for displacement measurement comprising microtransformers. The primary windings of the microtransformers are excited with an AC source with a frequency of several MHz. The microtransformers are fabricated in internal metal layers of an integrated circuit using a conventional 350 nm commercial CMOS process, along with corresponding circuits for the processing of the microtransformers' output signals. The major advantage of such system is its cost-effectiveness due to its straightforward fabrication and the absence of the need for an external field generator, such as permanent magnets at Hall Effect encoders or a light source at optical encoders.

In a linear incremental encoder application, microtransformer output signals are modulated by a metal measurement scale positioned over the integrated microsystem, resulting in a combination of amplitude and phase modulation. The integrated circuit employs a fully-differential measurement channel with three-stage amplification and a mixer implemented with a Gilbert cell: the signal is demodulated using synchronous demodulation.

A prototype microsystem was designed, fabricated and evaluated, demonstrating a sensitivity of 0.99 V/mm with a copper target at an approximate microsystem-target distance of 200-250 µm.

Keywords: inductive sensor; eddy-current sensor; displacement sensor; ASIC; microtransformer; linear encoder

Sistem z mikrotransformatorji za inkrementalno merjenje linearnega pomika

Izvleček: Prispevek obravnava induktivni mikrosenzorski sistem za merjenje pomika na osnovi mikrotransformatorjev. Primarna navitja mikrotransfomatorjev so vzbujana z izmeničnim virom frekvence nekaj MHz. Mikrotransformatorji so izdelani v internih metalnih slojih integriranega vezja, proizvedenega s konvencionalnim 350 nm komercialnim CMOS procesom, pridružena pa so jim tudi ustrezna vezja za procesiranje izhodnih signalov mikrotransformatorja. Glavna prednost takšnega sistema je njegova cenovna učinkovitost zaradi preproste izdelave in odsotnosti potrebe po zunanjem generatorju polja, kot so npr. trajni magneti pri Hallovih enkoderjih oziroma svetlobni viri pri optičnih.

V aplikaciji linearnega inkrementalnega enkoderja so izhodni signali mikrotransfomatorja modulirani s kovinsko merilno letvijo, nameščeno nad integriran mikrosistem, kar se odraža v kombinaciji amplitudne in fazne modulacije. Integrirano vezje vsebuje popolno diferencialni merilni kanal s trostopenjskim ojačenjem in mešalnik, izveden z Gilbertovo celico: signal je sinhronsko demoduliran.

Zasnovan, izdelan in izmerjen je bil prototipni mikrosistem z doseženo odzivnostjo 0,99 V/mm pri bakreni tarči in oddaljenosti med tarčo in senzorjem približno 200-250 µm.

Ključne besede: induktivni senzorji; senzorji na vrtinčne tokove; senzorji pomika; namensko integrirano vezje; mikrotransformatorji; linearni enkoder

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1 Introduction

The main difference of inductive position sensing concept in comparison to conventional magnetic encoders (which are based on Hall or magnetoresistive sensors) is in the use of an alternating magnetic field instead of a stationary magnetic field; sensors employ the principle of electromagnetic induction.

Two major types of inductive sensors are used [1], [2]. The first type is a dual-coil structure, similar to a transformer. The first coil is connected to an AC source, inducing the voltage in the second coil. If a conductive object is moved close to the coils, eddy currents are induced in the object. Due to the loss of energy through this mechanism, the voltage in the secondary coil is reduced [3]. The effect on the secondary voltage is adversary in the presence of a ferromagnetic object, improving the magnetic coupling between the coils [3]. The second type is based on the change of the coil inductance under the effect of a nearby object: if a coil is wired into a resonant circuit, its oscillation frequency changes when the object moves [2].

Inductive sensors benefit from their insensitivity to dust, which stands out as a strong advantage in an industrial environment in comparison to the optical sensors [4].

Magnetic and optical position encoders can be fabricated as application-specific integrated circuits (ASICs). However, for their use, external placement of magnetic field source or light source is needed. Inductive sensors are free from this requirement, since they generate the high frequency magnetic field by an integrated inductor. In this paper, we present a microelectronic implementation of a prototype inductive linear position encoder, operating with a passive measurement scale. The sensor elements are realized as microtransformers with the accompanying electronics fabricated together with the microtransformers in an ASIC using an unmodified 350 nm CMOS process.

2 Design

The discussed system operates similarly as a linear variable differential transformer (LVDT), as well as an eddy current sensor [1–3], [5]. The sensor is scaled to the size of a typical integrated circuit (several square millimeters). The design of the microtransformer setup used in the sensor is shown in Figure 1. Figure 2 displays the differential operation of the microtransformer. When a full half-period of a ferromagnetic scale is positioned over the first microtransformer, the coupling between the primary and the secondary winding is the strongest for this microtransformer. Contrarily, the coupling is then the weakest for the second microtransformer as the void half-period is positioned over it [2], [3].

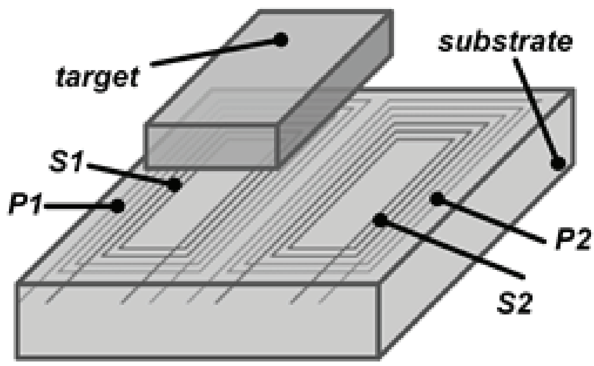

Figure 1: The structure of a microtransformer pair (P – primary, S – secondary winding) [2].

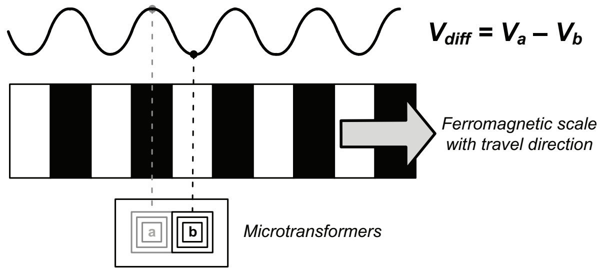

Figure 2: The differential operation of a microtransformer pair [2].

The differential voltage of the microtransformer pair V_{diff} is obtained by subtracting the secondary voltages of microtransformers V_a and V_b [3]. In the described situation (Figure 2), V_{diff} amplitude is maximal. As the scale

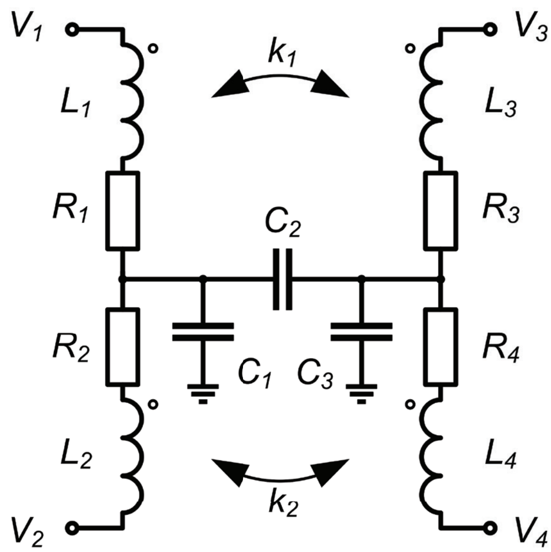

Figure 3: A model circuit of a microtransformer [3].

moves, the outputs change periodically. It should be noted that for a conductive (non-ferromagnetic) scale, the operation is adversary [5]. When a microtransformer is completely covered with a part of non-ferromagnetic metal, its induced voltage is minimal due to energy dissipation in the scale through the mechanism of eddy currents [3].

Using the presented differential principle, the signals which are common to both microtransformers in a pair (such as EMI and the capacitively transferred voltage) are subtracted [5].

The general design of the microsystem is presented in Figure 5 (a). It consists of a silicon die comprising the microtransformers along with analog front-end electronics for the generation of the differential signal [3]. The microtransformers are fabricated using standard CMOS technology metal layers. The total layer count is four. The external dimensions of the microtransformer primary and secondary windings are 755 by 500 µm and 576 by 314 µm, respectively [3]. Therefore the scale period *P* is 1 mm. Each winding of a microtransformer has 45 turns: three layers with 15 turns per layer are used, while the top metal layer is used for routing the connections [3]. The winding structure for a single winding is shown in Figure 4. Such structure is used for reducing the interwinding capacitance [3]. A model circuit of a microtransformer is shown in Figure 3, with the accompanying component values given in Table 1. Such circuit is insufficient to model the effects of the measurement scale on the output voltage of a microtransformer. So, finite element modeling was used to acquire the modulation characteristics as described in [3], [6].

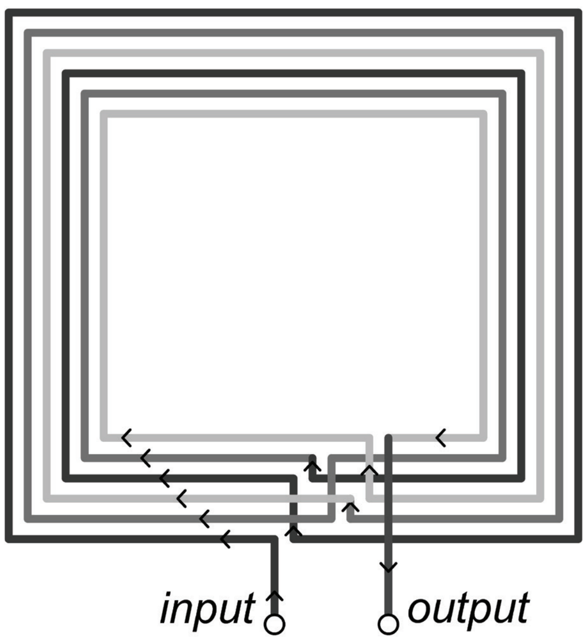

Figure 4: The microtransformer winding design [3].

Table 1: Component values in the model circuit [3].

Components	Value
R_1 , R_2	2657 Ω
R_3 , R_4	1816 Ω
L_1 , L_2	1.16 µH
L_3 , L_4	658 nH
C_1	3.55 pF
C_2	3.4 fF
C_3	2.39 pF
k_1 , k_2	0.429

To improve the signal-to-noise ratio of the system, the output signals of the coils with same position relative to the scale period can be summed, as shown in Figure 5 (b). The primary windings are wired in parallel [2].

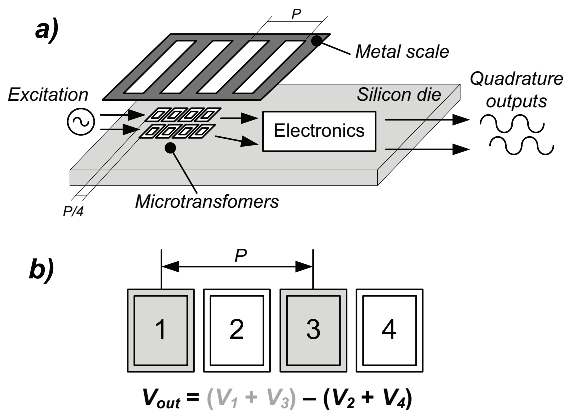

Figure 5: (a) A block representation of the presented microsystem with a metal scale of period *P* and quadrature output signals. (b) The implemented summation scheme [2].

The device comprises two channels shifted for a quarter of the scale period, i.e. quadrature output signals [3]. The quadrature principle is commonly employed in position encoders (e.g. optical [7] and Hall devices [8]), relying on (multiples of) two sensor elements with their position shifted by a half of the primary coil width (i.e. ¼ of the scale period *P*). Observing the phase shift of the quadrature signals allows the determination of the movement direction. If the signals have a sinusoidal shape, the arctangent function of their amplitude ratio enables a straightforward calculation of the displacement inside a single half-period [3].

$$x = \arctan\left(\frac{\sin x}{\cos x}\right) \tag{1}$$

A block diagram of a single measurement channel as implemented in the integrated circuit is shown in Figure 8. A fully differential channel setup is used, with the subtraction of the positive and negative microtransformer output signal performed at the end of the chain (Stage 3).

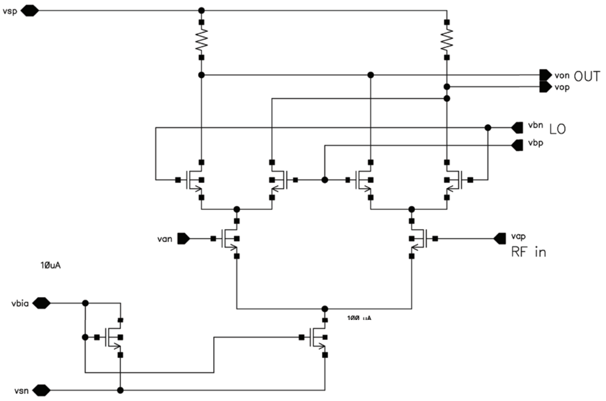

Figure 6: The Gilbert cell mixer implemented in the ASIC [6].

The first amplifier is wideband (72 MHz GBW), employing telescopic topology [3]. Then, the signal is mixed down to DC using a differential Gilbert cell CMOS mixer [6], shown in Figure 6. In the next two stages, signals are amplified at the baseband, also filtering out the remaining HF signal components [3].

3 Evaluation

To evaluate the performance of the microsystem, it was placed on a mechanical micromanipulator controlled by a computer, which was used to displace a measurement scale. Two scales (Figure 7) were used: scale (1) was made by laser cutting from transformer steel sheet (0.35 mm thickness), and the second (2) was fabricated as a PCB (35 µm copper thickness) [3]. Due to the presence of gel coating needed for the IC protection, the thickness between the scale and the surface of the IC was no less than 250-300 µm [3].

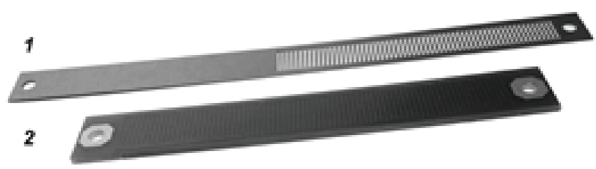

Figure 7: Scales used for the evaluation [3].

First, the excitation frequency and the phase of the mixing signal were swept to determine the optimal parameters. The maximal peak-to-peak amplitude of the output signal was chosen as the figure of merit [3].

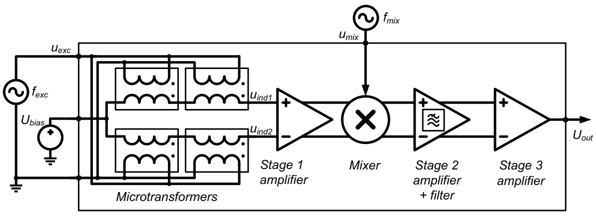

Figure 8: a block diagram of a single measurement channel implemented in the ASIC [3].

The output characteristics were recorded at the optimal excitation frequency f_{exc} and mixing signal phase φ_{mix} for the copper and steel scale with 20 µm positioning step. The results are given in Figure 9. The sensitivity S of the microsystem is defined (Equation 2) as the change of the output peak-to-peak voltage over a scale period P [3]:

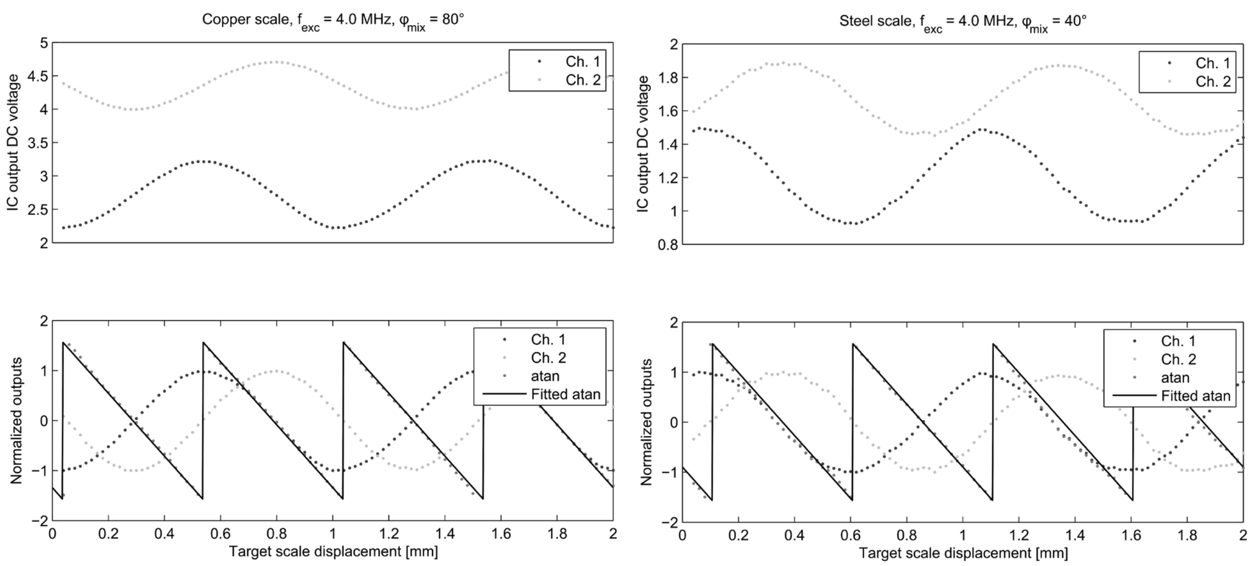

Figure 9: ASIC characterization results for both scale types. Results are compared to an ideal arctangent function.

$$S = \frac{\Delta U_{pp}}{P} \quad \left[\frac{\text{V}}{\text{mm}}\right] \tag{2}$$

Sensitivities for the two scales as well as maximum and RMS values of the linearity error *E* are given in Table 2.

Table 2: Summarized measurement results [3].

	Copper scale	Steel scale
S (Ch. 1)	0.99	0.57
S (Ch. 2)	0.71	0.44
max (E)	18.79	33.05
rms (E)	6.89	11.32

4 Conclusion

The design and the evaluation of an integrated microtransformer linear position measurement system were demonstrated. The system was evaluated with two scale types. It was discovered that various scales have different optimal excitation frequencies and phases of the mixing signal [3]. Therefore, a system should be adaptable to support the variation of these parameters. Considering the microtransformer sensitivity as well as the linearity error, better results were observed with the copper scale.

In our future work, we intend to redesign the measurement channel to reduce measurement noise by moving the major part of the amplification to the first amplifying stage, and to implement an on-chip frequency and phase-tunable oscillator, resulting in a true single-chip linear position encoder, having a significant potential for the encoder industry due to its cost-efficiency.

5 References

1. M. Podhraški and J. Trontelj, “Design and evaluation of a microcoil proximity sensing microsystem,” *Conf. 2015 Proc. 51th Int. Conf. Microelectron. Devices Mater. Workshop Terahertz Microw. Syst. Sept. 23 - Sept. 25 2015 Bled Slov.*, vol. 2015, pp. 95–99, 2015.
2. M. Podhraški and J. Trontelj, “An integrated microtransformer system for displacement measurement,” *Inf. MIDEM*, vol. 46, no. 1, pp. 29–35, 2016.
3. M. Podhraški and J. Trontelj, “A Differential Monolithically Integrated Inductive Linear Displacement Measurement Microsystem,” *Sensors*, vol. 16, no. 3, p. 384, Mar. 2016.
4. A. J. Fleming, “A review of nanometer resolution position sensors: Operation and performance,” *Sens. Actuators Phys.*, vol. 190, pp. 106–126, Feb. 2013.
5. J. W. Bergqvist, Y. de Coulon, and H. de Lambilly, “Device for detecting position and movement by using magnetic field variation,” US6043644 A, 28-Mar-2000.
6. M. Podhraški, “Integrirani mikrosenzorski sistemi z mikrotuljavicami,” Univerza v Ljubljani, Ljubljana, 2016.
7. J. Rozman and A. Pletersek, “Linear Optical Encoder System With Sinusoidal Signal Distortion Below 60 dB,” *IEEE Trans. Instrum. Meas.*, vol. 59, no. 6, pp. 1544–1549, Jun. 2010.
8. H. V. Hoang and J. W. Jeon, “Signal compensation and extraction of high resolution position for sinusoidal magnetic encoders,” in *International Conference on Control, Automation and Systems, 2007. ICCAS ’07*, 2007, pp. 1368–1373.

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