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On-chip Microparticle Manipulation with Efficient Wireless Power Transfer

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Abstract

By optimizing both the sinusoidal AC signal and DEP driving pulse signal frequencies in the wireless on-chip microparticle manipulation system as well as using CMOS circuits under about 0.5-V supply, improvement of power transfer efficiency and reduction of the total system power consumption including the primary power supply module were achieved.

1. Introduction

In recent years, sensor and control circuits are integrated on a chip in order to make equipment more compact, inexpensive, and easy-to-use. Wireless power transfer can improve these features [1]. In addition, manipulation of particles and cells is also useful for efficient sensing [2]. Dielectrophoresis (DEP), in which particles move under the influence of a driving force generated by the gradient of the electric field intensity [3], is a promising technique for this purpose. Recent studies [2, 4] have demonstrated wireless on-chip microparticle manipulation without external electrical wires.

In this work, improvement of wireless power transfer efficiency is focused to reduce the total system power including the primary power supply module.

2. System Configuration

The DEP force $\langle F_{DEP} \rangle$ acting on particles of radius r_e in a liquid medium with permittivity ε_m is given by the following equations [2].

$$\langle F_{DEP} \rangle = 2\pi r_e^3 \varepsilon_m \, \mathrm{Re}[\underline{Ke}] \nabla E_{rms}^2 \quad (1)$$

$$\underline{Ke} = \frac{\underline{\varepsilon_p} - \underline{\varepsilon_m}}{\underline{\varepsilon_p} + 2\underline{\varepsilon_m}} \quad (2)$$

where E_{rms} is the effective value of the applied electric field, $\underline{Ke}$ is the Clausius-Mossoti factor, and $\underline{\varepsilon_{p(m)}}$ is the complex permittivity of particle (solution). To utilize a compact low-power CMOS digital driving circuit, pulse-driven DEP is used in place of conventional sinusoidal one [2].

To prevent the solution temperature from increasing due to the Joule heating of wireless power transmitter and the chip in addition to power transfer loss, the chip must be operated at a low supply voltage. In the wireless on-chip microparticle manipulation system (Fig.1), the sinusoidal AC signal received by the on-chip secondary coil, which is inductively coupled to an external primary coil, is converted to the on-chip DC supply V_{DD} (~0.5V) using the CMOS rectifier [5]. Similarly to the previous work [4], a 31-stage ring oscillator is used to produce the DEP driving pulse signal. The simple process variation compensation technique [6] can reduce the oscillation frequency variation through body biasing. To prevent the DC component of the electric field from causing electrolysis near the DEP electrodes, the DEP driving signals with about 50% duty are generated in the divide-by-two frequency divider. This system configuration is useful for optimizing both the sinusoidal AC signal and DEP driving pulse signal frequencies. To enhance the wireless power transfer efficiency, the AC signal frequency can be set higher. On the other hand, to reduce the chip power consumption, the DEP driving pulse signal frequency can be set lower.

3. Power Transfer Efficiency

For good power transfer, the series capacitor with the primary coil and the on-chip parallel capacitor with the on-chip secondary coil are used. Their capacitors can adjust resonant frequencies in the primary and the secondary sides. Based on the equivalent circuit in wireless power transfer (Fig.2), the maximum efficiency is expressed as [7]

$$\eta_{\max} \approx \frac{1}{1 + \dfrac{2}{\kappa\sqrt{Q_1 Q_2}}} \quad , \quad (3)$$

where κ is the coupling coefficient of the transformer, and Q_1 and Q_2 are Q values in the primary and the secondary coils. In this work, the frequency of the AC signal for the power transfer is set to 18 MHz, which is higher than those in previous works [2, 4]. From the electromagnetic simulation results of the designed transformers, Q_1, Q_2, and κ are estimated to 29, 18, and 0.18 at 18 MHz, resulting in estimated maximum efficiency of 67 % (Fig. 3). The circuit simulation estimates the efficiency of the power transfer about 37 % because of load impedance variation. The DEP driving circuits (the oscillator with compensation, the frequency divider, and the buffer) consume about 42 μW for the DEP driving at 4.6 MHz under 0.5-V supply.

4. Experimental Results

The test chip was fabricated using a 0.18-μm triple-well CMOS process (Fig. 4(a)). The chip size is 2.5 mm square. The external primary coil (Fig. 4(b)) has a magnetic sheet embedded on the bottom side to enhance the wireless power transfer efficiency [2]. The DEP driving signal (about 0.5 V, 4.6 MHz) through the wireless power transfer was observed (Fig. 5).

After dropping the $NaHCO_3$ aqueous suspension (conductivity: σ_m = 10 mS/m) containing polystyrene microparticles (diameter: 2 r_e = 10 μm) onto the chip, AC power (18 MHz) was provided to the chip through wireless power transfer to drive the electrodes for the DEP operation. Microscope observations before the DEP operation and after the operation start (Fig. 6) demonstrate that the polystyrene microparticles between the quadrupole electrodes are concentrated in the center, which indicates negative DEP (Re[$\underline{Ke}$] < 0).

3. Conclusions

In order to achieve easy-to-use on-chip microparticle manipulation, a chip that can manipulate microparticles by pulse-driven DEP in a solution without any external electrical wiring was designed. The fabricated chip demonstrates more efficient wireless power transfer than those in the previous works, resulting in reduction of the total system power consumption including the primary power supply module. The DEP operation under internal 0.5-V supply generated from the CMOS rectifier was also observed.

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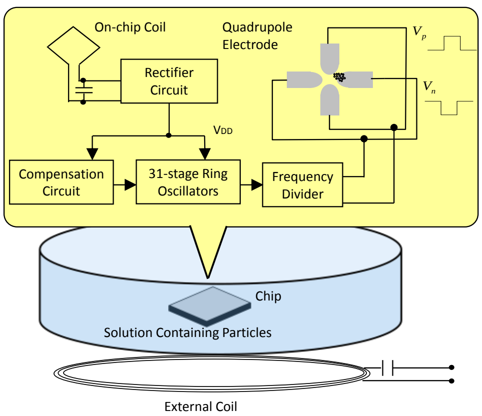


Fig. 1 Configuration and operating environment of wireless on-chip microparticle manipulation.

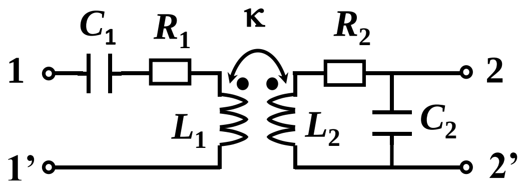


Fig. 2 Equivalent circuit in wireless power transfer.

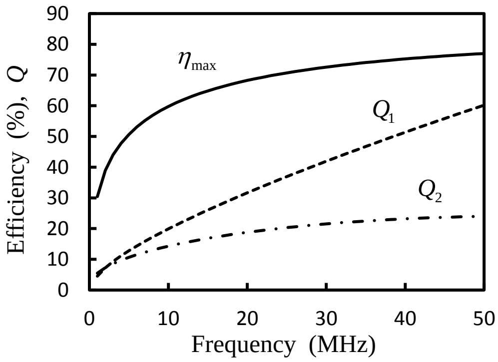
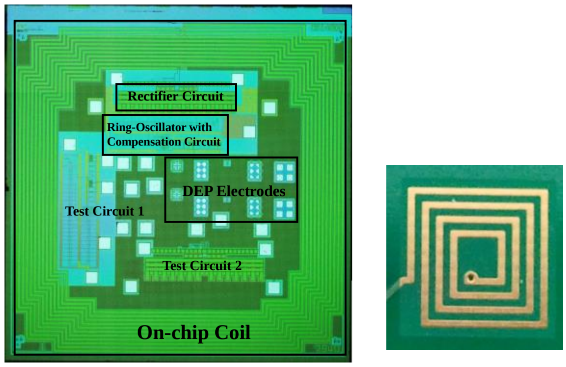


Fig. 3 Estimated values of transformer's parameters (Q_1 and Q_2) and maximum power transfer efficiency η_{max}.



(a) (b)

Fig. 4 Photographs of (a) fabricated chip and (b) primary coil with a magnetic sheet on the bottom side.

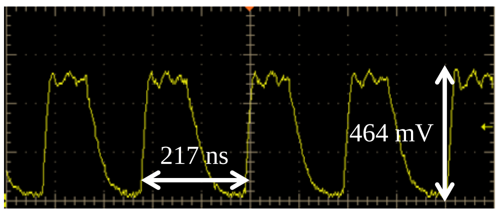


Fig. 5 Measured waveform of DEP driving signal on the chip.

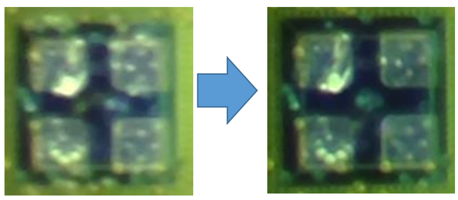


Fig. 6 Microscope observation of negative DEP on the chip using wireless power transfer.