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Towards efficient surface acoustic wave (SAW)-based microfluidic actuators

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ABSTRACT

The applicability of surface acoustic wave (SAW) based actuators was demonstrated for a variety of microfluidic tasks, including fluid mixing, particle separation, localized heating or fluid atomization. But as traditionally the main field of application lies in high-frequency telecommunication, SAW devices are only marginally optimized for microfluidics, especially in respect to an energy efficient operation. In lab setups incorporating SAW-based microfluidic actuators, insufficient energy efficiency resulting e.g. from interdigital transducers (IDTs) with inadequate electrical impedance, absorption of SAW power in vessel walls or maladjusted wavelengths, is often simply counteracted by an increase of the output power of the signal source. For the operation of portable or highly integrated devices, though, or for devices with high power needs, energy efficiency is crucial. Additionally, an inefficient mode of operation can result in severe device degradation.

In order to extend the performance of SAW actuators, we discuss different approaches regarding the optimization of their power efficiency and provide selected experimental results, highlighting the importance of the governing power loss effects. Depending on the intended microfluidic task, several of the demonstrated optimization strategies can be combined and – as will be shown – considerable improvements in the device performance can be achieved.

1. Introduction

Surface acoustic wave (SAW) devices have been successfully applied for various microfluidic tasks, including fluid mixing, droplet translation, fluid atomization and particle manipulation [1,2]. Crucial parameters for the functionality of such actuators are the available electrical power from the signal source and the efficiency of the energy conversion to the manipulated system, e.g. a microchannel or a droplet on the chip surface, and wave mode, e.g. a longitudinal pressure wave, respectively. In real-world systems, losses in the electric or acoustic regime reduce the input power supplied by the signal source and, thus, limit the SAW power for actuation. Fig. 1 summarizes the most important power loss effects together with a brief overview of suitable countermeasures.

The most simple and, therefore, most often applied approach to counteract the power loss and to realize the intended effect in the active region of the device is the increase of the power delivered by the high-frequency signal source. However, an increase of the power available by high-frequency sources is associated with a drastic increase of the costs and the geometric dimensions of the source itself. Additionally, a power loss associated with an inefficient device operation can cause a local temperature increase in the microfluidic device (due to parasitic power absorption and viscous damping), which can lead to severe degradation and malfunction in the device, and in the source (due to power reflection), which is especially critical for portable devices.

In order to minimize costs, system size and temperature-associated device degradation for portable devices and integrated high-power devices including SAW atomizers, acoustic tweezers and mixers, the available power provided by the source should be used with highest possible efficiency. In this work, five strategies to increase the power efficiency of SAW actuators addressing different power loss effects are demonstrated in individually adapted experimental setups. While the effects are addressed separately, the shown strategies can also be combined to further increase the efficiency of an intended task.

2. Optimization strategies for microfluidic SAW actuators

For all of the experiments, SAW chips with interdigital transducers (IDTs) consisting of subsequent layers of Ti (5 nm) and highly-textured Al (295 nm), were prepared on 128°YX-$LiNbO_3$

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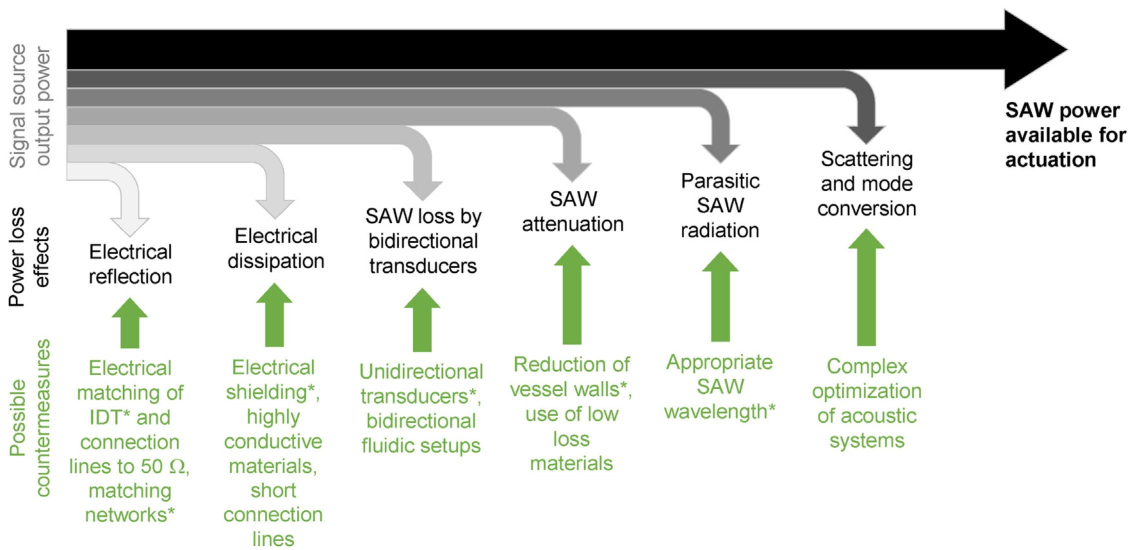

Fig. 1. Power flow chart and loss effects in microfluidic SAW devices, together with possible countermeasures; *indicates issues covered in this article.

substrate (128° rotated Y-cut lithium niobate with X-propagation direction) via electron-beam evaporation and lift-off technique.

2.1. Electrical optimization of interdigital transducers

The electrical impedance of an interdigital transducer is determined by material and design parameters, e.g. the substrate and electrode material, the IDT type, the aperture, the electrode width and height and the number of finger pairs. However, for most experiments, only the number of finger pairs can easily be chosen and, thus, can be used to adjust the impedance. For basic, uniform layouts comprising solid or split finger electrodes only, rather simple relations given in [3,4] can be used for simulation of IDT impedance (appropriate material data for usual SAW substrates are listed in [4]). Additional external boundary conditions, including thin dielectric films or a fluid layer on top of the IDT, have to be taken into account, when the electrical device behavior of more sophisticated designs is subject of optimization. Since the standard characteristic impedance for radio-frequency (RF) cables and generators is defined to be $Z_0 = 50\,\Omega$, the optimal impedance matching and therefore the highest energy conversion efficiency is achieved if the impedance Z of the SAW-device is equal to Z_0. In this ideal case, the scattering (or S-)parameter $|S_{11}|$ [5], which equals in practical cases the voltage reflection coefficient, is zero at the SAW excitation frequency, which means, that all electric power is converted to the surface acoustic wave – when the electric losses in the IDT itself are neglected. In all other cases, portions of the electric power supplied by the signal source are reflected at the device input and therefore not available for the liquid actuation. Noteworthy, the electrical connection between signal source and IDT (e.g. cable, stripe line) also has to be taken into account. A possible impedance mismatch as well as an input coupling of external transient fields will disturb electrical power transmission. The electrical connection should therefore be chosen as short as possible. An additional shielding might be useful especially for fluid-loaded IDTs due to the influence of varying fluid conductivity.

In order to make experimental results comparable, SAW devices have to be electrically characterized either by their impedance (or admittance) parameters or by their S-parameters. A characterization via the supply voltage only without mentioning the electrical properties of the device, as done in various scientific publications, is insufficient. Ideally, actuators are characterized by the SAW amplitude distribution in the actuation zone. However, while the measurement of the latter is only possible with expensive equipment (e.g. laser vibrometers), the electrical characterization can be easily achieved with standard RF equipment like a network or impedance analyzer. Preferably, the measurement and specification of the electrical performance of SAW devices is done in terms of their S-parameters.

$$P_{IDT} = (1\text{-}r_P) \cdot P_{Source}, \text{ with } r_P = |S_{11}|^2 = \frac{|Z - Z_0|^2}{|Z+Z_0|^2}$$

For single IDTs, the **reflection coefficient of power r_P**, i.e. the squared absolute value of the reflection coefficient ($|S_{11}|^2$) [5], is of special importance as it is a measure for the amount of power coupled into the SAW device in respect to the power supplied by the signal source.

2.1.1. Experimental

The electrical impedance of several IDT designs was optimized for a large range of wavelengths and apertures using a proprietary software based on the well-known coupling-of-modes (COM) theory [4]. Also taken into account were the acoustic and electric effects of additional SiO_2 passivation layers and, if possible, the direct IDT immersion in water ("wet" usage). In the experiment demonstrated here, two single λ/4-IDTs (wavelength = λ = 30 μm, aperture = w = 0.5 mm, number of finger pairs = N = 32 and 80, respectively), were produced and covered with a sputter-deposited SiO_2 (thickness 1 μm) in order to prevent possible corrosion of the IDT electrodes and to establish a surface with high biocompatibility on the piezoelectric substrate [6]. Thereby, the IDTs were optimized for dry usage (N = 32) or usage immersed in water (N = 80). The chips were placed on a custom chip holder and mechanically retained and electrically connected (Fig. 2a) using printed conductor boards (PCB) with stripe lines matched to 50 Ω impedance and gold-plated spring pins. Characterization of the electrical IDT behavior was carried out via S_{11} measurements by a vector network analyzer (VNA, Agilent E5071C) for three cases of IDT operation: (1) The initial state of the IDTs without any coating, (2) the IDTs covered with SiO_2 and (3) with an additional water droplet covering the whole IDT surface. Highly viscous photoresist was applied to the chip edges in the SAW path as damping material, i.e. to minimize the influence of acoustic reflections on the electrical behavior.