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Design of Micromachined Resonators for Fish Identification

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Abstract— **The ID tag presented here was designed to give a tag of small size that could be produced at a low prize, and that could be read remotely in live fish, even in seawater. The last condition precludes use of electromagnetic waves for interrogation of the tags, and acoustic interrogation is then a clear alternative. The solution presented is a passive tag with a set of acoustic resonances that may be detected acoustically.**

The tag operates in the 200 to 400 kHz range. The identity of the tag is given by a unique combination of resonances in this frequency range. For the tags presented here there are five resonances per tag. If five or more resonances are chosen from a predetermined set of say 17 resonance frequencies, a total number of at least 3000 to 4000 different tags are available. This is adequate for classification of fish at the batch level in fish farms, or of local wild fish tribes.

The resonators on a tag consists of a thin, nominally 500 nm thick silicon nitride membrane suspended over separate evacuated cavities, made by bulk silicon micromachining. The resonators were designed to have Q-factors in the range 27 to 35 with viscous losses in the water neglected.

The resonators have been measured in water and in dead or live anesthetized fish from distances up to 30 cm. Sharp resonances in fair accordance with the tag design were achieved. Some alterations of the tag response with change of the angular orientation of the tag relative to the ultrasound beam are seen. This is also theoretically expected.

Keywords-component; ID-tag; acoustic resonator; bulk micromachining.

I. INTRODUCTION

There are several kinds of ID-tags available for use in tracking fish. Among them are the coded wire tag (CWT) and the passive integrated transponder (PIT) tag. The CWT is a steel wire typically 0.25 mm in diameter and length 1.1 mm which is marked with rows of numbers for coding. It is put into the snout of the fish. Its advantage is low cost and high reliability [1], while its main disadvantage is that it requires the fish to be slaughtered for the CWT to be retrieved and read under a microscope. The PIT is a passive RF-tag, and if the frequency is low enough it can be read at a distance of 0.5-1 m especially in fresh water [2]. It is mainly used for research purposes as the size is large and the cost may be high.

The purpose of the development reported here was to come up with a low cost tag with small size that could be read from a distance in-vivo. The tags are passive and based on acoustic resonances, well suited to be used underwater. It may be used to identify individual fish or fish batches in fish farms. In this case one would typically identify fish as they pass through a tube when fish is pumped from one cage to another in fish farming. A much more demanding task would be to identify escaped individuals from fish farms that may mix with the indigenous populations in rivers. The purpose would be to identify which fish farm that is the source of the escaped fish. Here detection should be done over much larger distances, several meters or more instead of tens of centimeters. The envisioned system may easily give several thousands of different ID-tags, but both the tags and notably also the detection and the detection systems could be much simpler if one is aiming for a lower number of different tags. For many applications a few hundred different tags would probably be sufficient.

The tags presented here are made by bulk silicon micromachining, but also surface micromachining technology could be used. These production technologies are well suited for accurate high volume production at low cost, and could provide cheap tags. The tags also prove durable, and reuse of used tags might be possible.

In the following we briefly discuss coding with resonances and outline the design of the tested tag. We further discuss experimental results showing how the tags perform in water and in live anesthetized fish in water.

II. THEORY

A. *Coding with resonances*

In this chapter we will assume that we are able to detect the resonances on a tag with resonators, and the resonance frequency of each resonance. Due to fabrication tolerances and factors such as pressure dependence of the resonance frequency of a resonator and effects of aging, it is reasonable to assume that one would have to use one of the resonances for frequency calibration purposes. To be easily recognized this could be the lowest resonance frequency on the tag. If we assume that there are up to N additional resonance frequencies on the tag, and that these are chosen from a set of M predetermined frequencies, the number of different tags that could be generated is:

$$N_c = \sum_{n=1}^{N} \frac{M!}{(M-n)!n!} \qquad (1)$$

The sum is taken over the number of additional resonances that is really present on the different tags. If we insist that all tags should have N additional resonances, the sum disappears, and n should be replaced by N. To be able to identify the frequencies on a tag easily, this may be desired. If four out of totally five resonance frequencies on a tag is chosen from a set of 16 possible frequencies, M = 16 and N = 4, we get a set of 1820 different tags. If we in addition allow tags with from one to three resonances in addition to the reference, we get 696 additional tags, and totally 2516 different tags. If there is no need to use one resonance for calibration purposes, we could choose one to five frequencies out of a set of 17, and get *9401* different tags. We see that it is possible to obtain a rather high number of different tags even with a low number of resonance frequencies on each tag. The optimum number of frequencies on each tag, and the optimum number of available resonance frequencies for a given application will depend on a number of factors as detection costs, fabrication costs, and possible limitations in the size of each tag. This will not be discussed any further here.

B. Resonator Design and Tag Fabrication

The resonators were designed using a simple theory where the acoustic fields around the resonator is approximated by the well known fields from a pulsating spherical acoustic source [3]. To calculate the pressure on the membrane surface, we assume that it would be as from a spherical source with the same volume change as for the vibrating membrane, taken at a radius of about 17.5 % of the side edge of the membrane from the source centre. This connection is given in (2), where ΔV is the amplitude of the pulsating volume of the source, r is the distance from the centre, ω is the angular frequency, ρ is the density of the medium, water, and k_0 is the plane wave wave-number for pressure waves in water.

$$p = -\frac{\Delta V \omega^2 \rho}{4\pi r} \exp(-ik_0 r) \qquad (2)$$

One of the fabrication constraints is that all the resonator membranes on a tag must be made from the same film, meaning the same material and the same thickness. For a given desired resonance frequency, $\omega_0 = \omega$, we find the desired side edge l_s for the resonator as follows: For a given set of membrane properties we determine through iterations the l_s that gives a deflected volume ΔV for the membrane at a pressure given by r = 0.175 l_s in Eq 2. This defines the resonance frequency of the resonator. Another important property of the resonator is its Q-value. It is given by the real part of the acoustic impedance at r, (2), divided by the imaginary part of the impedance, and is $1/k_0 r$. The real part of the impedance indicates radiation from the pulsating source, see [3]. To obtain desired Q-values of the resonators we may have to redo the iteration above with different properties for the film. One will normally find that for the same film properties, resonators at different frequencies get different Q-values, even when additional losses are neglected. Our design was done using data for a 0.5 µm thick silicon nitride film with a built in stress of 300 MPa. It showed Q-values of the resonators ranging from 35 at 200 kHz to 27 at 400 kHz. The Q decreases with resonance frequency as the ratio of l_s to the wavelength at resonance also decreases with frequency. The side edges of the quadratic designed resonators range from 195 µm to 126 µm.

Some modeling has also been done where we take into account more correctly the real geometry of the tag resonators. It assumes the tag surface to be fixed with its actual size. These calculations give resonance frequencies that are about 17 % lower than the original model. To compare with the original model we should let ΔV be two times the volume depleted by the membrane, as it is mainly feeding a half sphere, and use r = 0.24 l_s. The Q's of the resonators are correspondingly reduced.

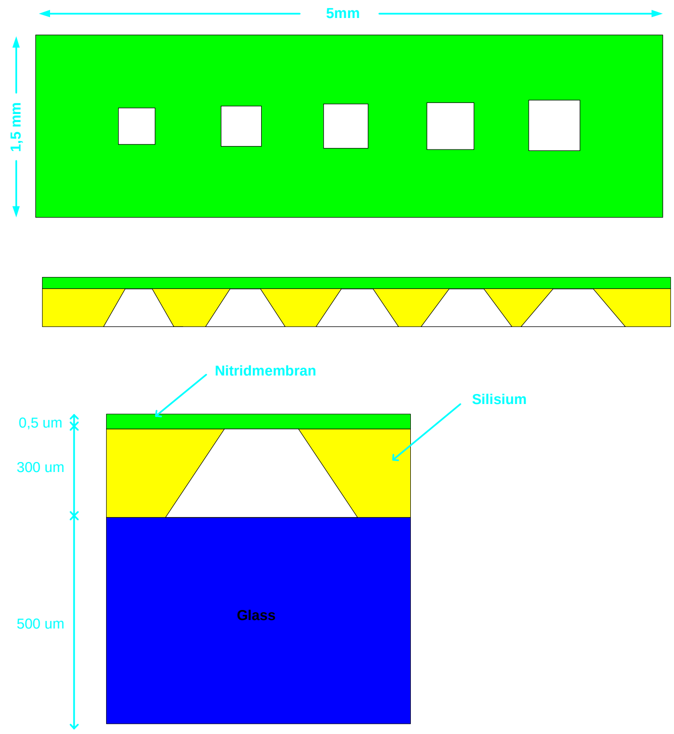

Fig. 1.: Outline and side view of the silicon crystal with membranes, top, and end view of the final tag, bottom.

The outline of the tag is shown in Fig. 1. Five resonators were put on each tag, along a line at the centre of the tag, to make the tags rather long and narrow. The tags were 5 mm long, 1.5 mm wide and about 0.8 mm thick. The centre to centre distance between resonators on the tag was chosen to be 1 mm. As this distance is rather large compared to side edge of the resonator membranes, it was not expected that there would be any strong influence on resonance properties of a given resonator from its neighbors. Hence no changes were made in the membrane dimensions for a resonator with a given desired resonance frequency, depending on the resonance frequency of its neighbors.

In spite of this we do expect that the distance between resonators with close resonance frequencies will influence the reflection pattern from the tag. This is due to the fact that if we excite the tag with a wave propagating along the long dimension of the tag, the different membranes will be excited with different phase. If the reflected signal is detected at the transmitter, the signal reflected from different resonating membranes will get different phase shifts back to the receiver. At 0.4 MHz and with 1 mm position difference, the phase difference may be up to 96 degrees in both excitation and detection.

Hence the reflected signal from two different resonators may interfere with almost all possible relative phases for a some of the resonators, depending on the angle at which the resonator is detected. If the transmitter and the detector are positioned in opposite directions of each other as seen from the resonator, all these phase shifts would cancel. However the receiving system would have the difficult task of detecting the reflected signal from the resonator on top of the direct signal from the transmitter, and hence this is possibly not a good solution. A better solution may be to position the receiver at some angle off the opposite direction of the transmitter. If an offset angle of 30 degrees is chosen, the receiver could be shielded from the direct exciting signal, while the maximum phase difference is reduced from up to 2x96 degrees to about 13 degrees. This would give a much more standardized signal from a given tag, but would probably not be applicable in many cases. Another solution to the problem would be to let the detector system search for different characteristic reflection patterns from a given tag, which covers the different forms the echo from a given tag might take, depending on excitation (and detection) angle.

The ID-tags, see Fig. 1, were made by a bulk micromachining process, including the following steps. First the silicon nitride film was deposited by LPCVD (Low Pressure Chemical Vapor Deposition) on a 280 µm thick {100} oriented silicon wafer. Then appropriate etching openings were made on the back side of the wafer, and the resonator cavities were formed by etching through the wafer using an etchant with high selectivity against etching silicon in the <111> direction and against etching the nitride film. The cavities were then closed by bonding the back side of the wafer to an about 500 µm thick Na glass plate using anodic bonding. This gives a final stack of a thickness of about 0.8 mm. On each tag there were 5 resonators. They were put at a centre to centre distance of 1 mm along the tag. The rather large distance between the resonators was chosen to be able to accommodate a few resonators at lower frequencies. These are not discussed further here.

III. EXPERIMENTS

The tag was tested and verified during 2002 and 2003. The experimental setup is illustrated in Fig 2. Transmit pulses are defined in Matlab and transferred to the signal generator *(Agilent 33120A)*, using RS232 communication. The signal generator drives the transmitting transducer directly. Ultrasound pulses are scattered by the tag, and the echoes picked up by the receiving transducer. Both transducers have centre frequency 250 kHz and diameter 38 mm (*GE Panametrics V1012*). Echo signals are amplified by a preamplifier *(Reason VP1000)* and registered on the digital oscilloscope *(Agilent 54622A)*, and the digitized traces transferred to a computer for processing in Matlab.

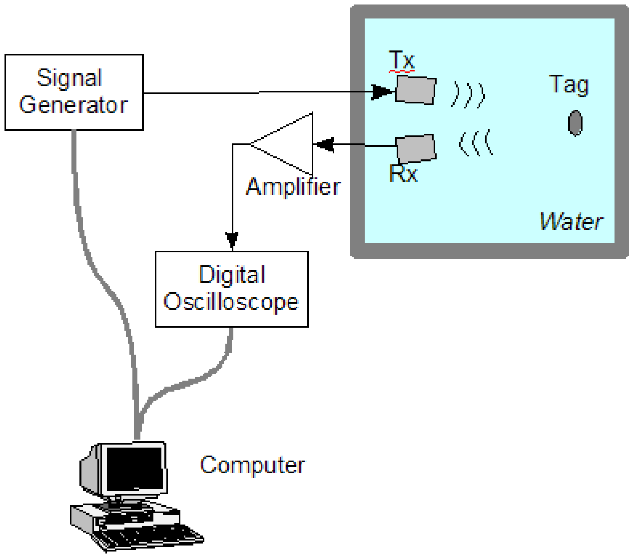

Figure 2. Illustration of the experimental setup

The first experiments were done transmitting a set of single frequency pulses, spanning the range from 150 to 500 kHz. To reduce measurement time, this was later changed to transmitting one pulse of length 1 ms, containing a continuous sweep over the frequency range.

The verification was done in three steps:

1) Test with ID chips in water
2) Test with ID chips, mounted in fish tissue, in water
3) Test with ID chips, mounted in anesthetized fish, in water.

The step-wise progression was important in order to determine whether the fish body would have negative influence on the received signal, compared to a free chip. Sharp resonance peaks in fair accordance with the chip design were achieved, and the results were repeatable also with small changes of the chip position in relation to the ultrasound beam. Chips with the same resonance cavities from the same series are in good

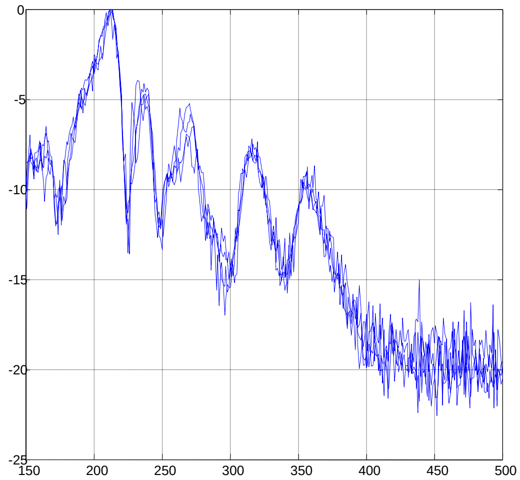

Fig. 3: Four overlaid measurements on a chip suspended in water showing the five resonances (x-axis: kHz, y-axis: dB). The curves are not compensated for the transducer responses.

agreement (see Fig. 3), whereas chips from different series differ a bit according to deviations in membrane thickness and size. The membrane size is due to the fabrication method strongly dependent on the thickness of the silicon wafer.

The measurements given in Fig. 3 and 4 are made on a tag with nominal side edges of 175, 161, 149, 137, and 126 µm, and with the nominal resonance frequencies of 238, 271, 308, 351, and 400 kHz. We see that the resonance peaks in the echo recordings appear at lower frequencies than the design values, but not by quite as much as the improved analysis indicates. This may as well be due to uncertainties in the real membrane parameters, as errors in the analysis. We also see that there is a marked drop in amplitude of the reflected signal with frequency. This may have three causes. We have already mentioned interference between signals from different resonators on the tag. Another is the expected drop with frequency in scattering from a small resonant structure, at 6 dB per octave. A third cause is the influence of viscous losses in the acoustic field close to the resonator, which will increase with frequency. In water the loss differences are about 4 dB higher than expected, and in fish about 9 dB higher. The added differential losses in the fish could come from added dissipation in the fish, but also from other sources as anisotropy in the radiation pattern.

As shown in Fig. 4, the signals from a fish without a chip (red) and with chip (blue) are significantly different. The resonators can be detected and the measurements are repeatable. However, with the equipment at disposal the fish had to be kept in the beam focus during the measurements.

The chips have shown no signs of alterations of their resonances during the test period, even if they have been used several times in different fish. Some phenomena like change of reflected signal pattern due to change of angle between chip

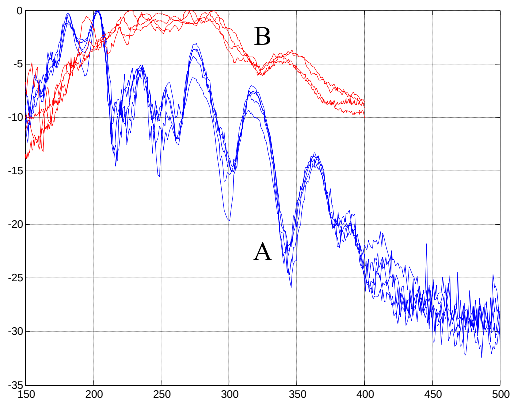

Fig. 4: Reflected signal from fish with ID-chip (blue, A) and without ID-chip (red, B), all normalized to 0 dB peak level.

and beam have been observed, and will be further investigated later.

IV. Conclusion

A passive ID-tag has been designed and tested that can be read remotely under water using acoustic waves. It is small, and made by micromachining techniques, and hence could be cheap. It may be used for tagging of fish. The tag operates in the 200 to 400 kHz range, and its identity may be read by detecting the resonance frequency of acoustic resonators present on the tag. Resonance frequencies are in fair accordance with analysis. We have shown that echoes from the tag may be detected both in water and in fish. The difference in echo amplitude between echoes from high and low frequency resonators seems to be larger in fish than in water. This may probably be attributed to additional losses in the fish. We have also seen that the tag response depends on the orientation of the tag with respect to the acoustic beam inquiring the tag.

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