Lateral Coupling in Silicon Cochlear Models

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***Abstract*— Drawing inspiration from biological studies, we have developed a novel silicon cochlea model which better accounts for the effect of local fluid coupling on the basilar membrane. This fluid coupling is emulated by coupling an extra wideband filter to each narrowband filter in the array. In this paper we present some of the biological background and give a short survey of earlier silicon cochlea models. We then briefly discuss the bandpass-filter element used in the circuit before presenting our silicon cochlea model along with measurements of the performance of a single filter tap.**

I. Introduction

Over the last several decades there has been increasing demand for portable electronics. Low power consumption is an important constraint for these battery-powered devices, many of which incorporate some form of audio processing. This interest in low-power signal processing has provoked a renaissance in analog circuit design. In neuromorphic engineering, inspiration is drawn from biology in hopes of achieving performance-per-energy-usage on par with biological systems.

One biological subsystem of interest to audio processing is the cochlea, and several circuits have been developed which model the cochlea, including [1]–[6]. The cochlea is the front-end of the biological auditory system. Accordingly, a circuit which accurately models the functionality of the cochlea will provide a low-power audio processing front-end. Such a front-end is well suited for audio-processing applications like speech recognition [7], noise suppression [8], or sound localization [9]. In addition, a low-power, biologically plausible, audio front-end is of interest for hearing aids and cochlear implants.

In this paper, we present a silicon-cochlea circuit which more precisely models the effects of local fluid coupling on the basilar membrane. This modeling effect results in a lateral coupling of resonators in an array of bandpass filters, as shown in Fig. 1, which in turn produces sharper high-frequency slopes, much like biology.

All data in this paper are from integrated circuits fabricated on 0.5μm processes available through MOSIS.

II. Biological Motivation

The cochlea acts as the audio front-end in the biological auditory system. Sound waves cause a displacement of the basilar membrane, and this mechanical vibration is transduced to bio-electrical signals which are transmitted to the brain. Frequency decomposition occurs in the cochlea due to the varying stiffness and width of the basilar membrane. The stiffness of the membrane decreases from the outermost portion of the cochlea to the innermost portion. Sound waves traveling through the cochlea have decreasing velocity due to the stiffness gradient. As the velocity of the sound wave decreases, so does the wavelength. This process results in a position-dependent frequency response along the length of the basilar membrane.

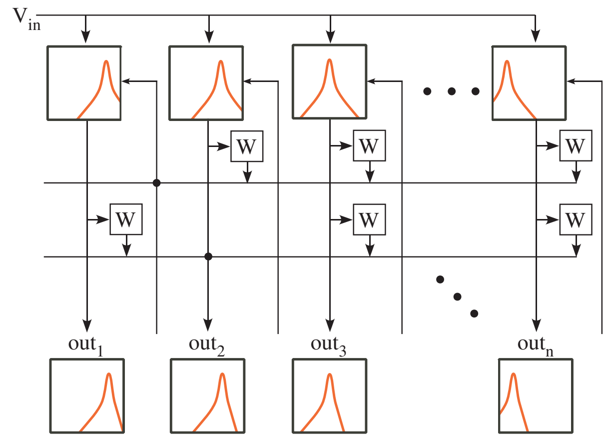

Fig. 1. Lateral coupling of bandpass filters to achieve a frequency response similar to the cochlea. An array of bandpass filters have their outputs coupled to the input of the other filters. This effectively subtracts the the response of the neighboring filters. By varying the weight of the connection between filters, the output can have the desired cochlea-inspired frequency response. In this case, the higher-frequency filters are weighted more than the lower-frequency filters, resulting in the asymmetrical frequency response seen in the figure.

An interesting aspect of the cochlea is the local fluid coupling that occurs [10]. When the basilar membrane undergoes motion in response to an incident sound wave, the motion of the basilar membrane causes a flow in the fluid surrounding it. This fluid flow partially inhibits the response of neighboring portions of the basilar membrane, therefore sharpening the response of the basilar membrane. In effect, the high-frequency slopes become far greater than would be achieved through a stand-alone resonator, and the overall shape of the tuning curves, or analogously the frequency response, becomes asymmetric about the center frequency with steep high-frequency slopes [11].

III. Silicon Cochlea Models

Silicon cochleae attempt to model the frequency decomposition that occurs in biological cochleae. Early silicon-cochlea

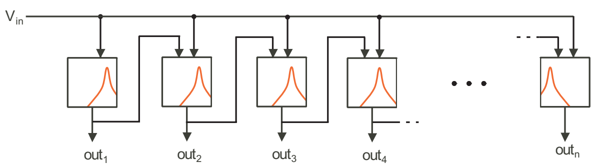

Fig. 2. Lateral coupling of higher-frequency filters becomes a cascade of filters. Large cascades lead to accumulation problems, such as noise, and should, thus, be avoided. However, this cascade approach should not have as severe problems with accumulation since the lateral coupling has a relatively small gain as compared to the input each filter receives from V_{in}. Also, only a small range of frequencies are passed to the neighboring stages, and, thus, only the noise from those frequency bands are passed to the neighboring stages. Additional lateral coupling can be used from additional stages preceeding the filter of interest. As a result, the filter may receive lateral coupling from several of the previous filters.

circuits modeled the wave-propagation nature of the basilar membrane via a cascade of lowpass filters [1]–[4]. Second-order sections with moderate resonance, or Q, were used for lowpass filters, and the corner frequencies of the filters decreased while moving through the cascade. The transfer functions of the cascaded filters multiply together to yield a very steep transition band. While the cascaded lowpass-filter approach provides the remarkably steep high-frequency slope seen in biology, there is no attenuation of low frequencies, although some models utilized differentiation to achieve a pseudo-bandpass response [2], [3]. In practice, this approach had significant issues such as noise accumulation and the risk of losing functionality of a large portion of the system if one stage stopped working.

Another approach to modeling the cochlea is simply an array of bandpass filters [12], and several silicon examples are [5], [6], [13]–[15]. Each filter is tuned to a different portion of the audio band and all filters receive the same input. The filters have a narrow bandwidth with moderate- to high-Q. Steeper roll-offs can be achieved by using higher-order filters. While this model does not suffer from cascading issues discussed in the previous section, it does not produce an asymmetrical frequency response as seen in the cochlea.

To model the inhibitory effect of fluid coupling, adjacent filters in the bandpass array can be weighted and subtracted from the filter of concern. Figure 1 demonstrates an electronic equivalent to fluid coupling. In this system, a weighted sum of the outputs of each neighboring stage are added to the input of each individual filter. The result is an effective subtraction of the response of the neighboring filters and, thus, a greatly sharpened frequency response from the filter of interest.

While a weighted subtraction on both the low- and high-frequency sides of each particular center frequency would help to sharpen the transitions to the stopband, this lateral coupling is most prominent in the frequencies above the center frequency in biological systems [10]. If only the higher frequencies are to be coupled in, another way to view this system is shown in Fig. 2. Each filter in the array receives the common input to the entire system and also the output from the previous stage, which has a slightly higher center

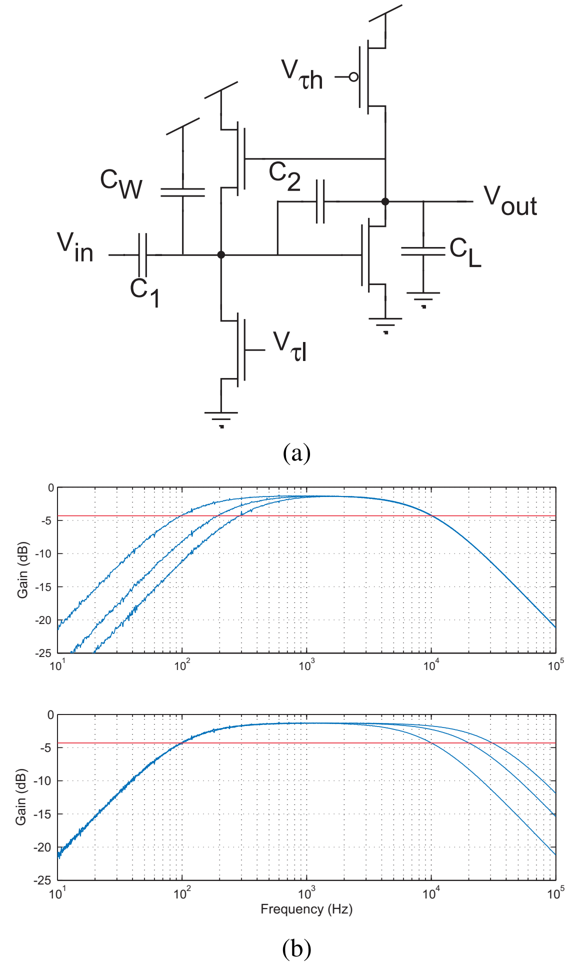

Fig. 3. (a) C^4 schematic. $V_{\tau l}$ controls the low corner frequency and $V_{\tau h}$ controls the high corner frequency while the gain depends on the ratio C_1/C_2. (b) Wideband response of C^4 demonstrating the capability to tune each corner frequency independently.

frequency. Added input lines could also come from previous stages, as well; however, too many added input lines could cause difficulties in designing the IC for fabrication.

Some of the problems with this approach are illustrated in Fig. 2. One major advantage of the array of bandpass filters in parallel was the minimization of accumulation problems that came as a result of a cascade. In the early cascade models [1]–[4], significant problems resulted from cascading many lowpass filters. The design of Fig. 2 is basically a cascade that also has a common input. This design will also suffer from similar cascade problems, though it will not be as severe since the bandpass filters are passing only the frequencies and noise within their own particular passband.

IV. C^4 Bandpass Filter Element

The bandpass filter element used for the cochlea model described in the next section is the capacitively coupled current conveyor (C^4) [16]. The C^4 (Fig. 3(a)) is a compact, low-power, bandpass filter circuit. Each corner frequency can be

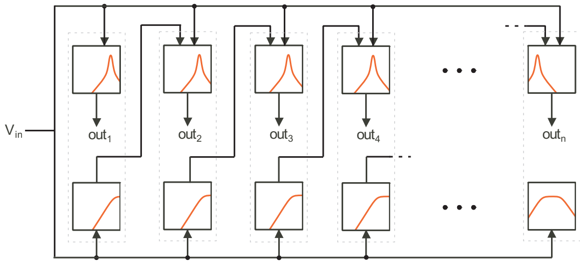

Fig. 4. Lateral coupling of higher-frequency filters with "dummy" filters. Each filter tap includes an extra filter that is tuned to have a wider bandwidth. This dummy filter receives the same input, V_{in}, as the other filters, but only the dummy filter passes its output to the next filter tap. As a result, this technique has no cascade longer than two filters at any given point. Also, the wide-band filter produces the effect of several cascaded filters since it represents the sum of the preceeding filter stages.

individually tuned. $V_{\tau l}$ controls the low corner frequency and $V_{\tau h}$ controls the high corner frequency. Figure 3(b) shows that tuning of the corner frequencies may be achieved independently of each other. Programmability can be achieved with the C^4 by use of floating gate transistors to set the bias currents through M_2 and M_3 [17].

The transfer function for the C^4 is

$$\frac{V_{out}}{V_{in}} = -\frac{C_1}{C_2}\frac{s\tau_l\,(1 - s\tau_f)}{1 + s\left(\tau_l + \tau_f\left(\frac{C_O}{C_2} - 1\right)\right) + s^2\tau_h\tau_l} \qquad (1)$$

where the time constants are given by

$$\tau_h = \frac{C_T C_O - C_2^2}{C_2 g_{m4}} \quad \tau_l = \frac{C_2}{g_{m1}} \quad \tau_f = \frac{C_2}{g_{m4}} \qquad (2)$$

and where the total capacitance and the output capacitance are given by $C_T = C_1 + C_2 + C_W$ and $C_O = C_2 + C_L$, respectively. The feedthrough time constant given by τ_f typically has little effect on the circuit in the region near the passband.

V. Lateral Coupling

The lateral-coupling model presented in this paper achieves the desired response with a minimal amount of cascading. This lateral coupling can be done by adding an extra "dummy" filter along with each filter tap that receives the same input as its associated filter but sends its output to be subtracted from the next stage, as is shown in Fig. 4.

This dummy filter is a lower-Q filter than its associated bandpass filter. Also, this filter is set to have a wider bandwidth than its associated filter so that it approximates several of the neighboring filters since the sum of all the higher-frequency filters is essentially the same as a single wide-band filter. The circuit-level schematic of this type of configuration is shown in Fig. 5. Specifically, this schematic represents the C^4 from the filter tap of interest and the wide-band, lower-Q C^4 from the next higher-frequency stage. The buffered output of the dummy filter is capacitively coupled to the main C^4. During a tuning, or programming phase, this added capacitor is connected to V_{dd} so that it effectively adds to the capacitance

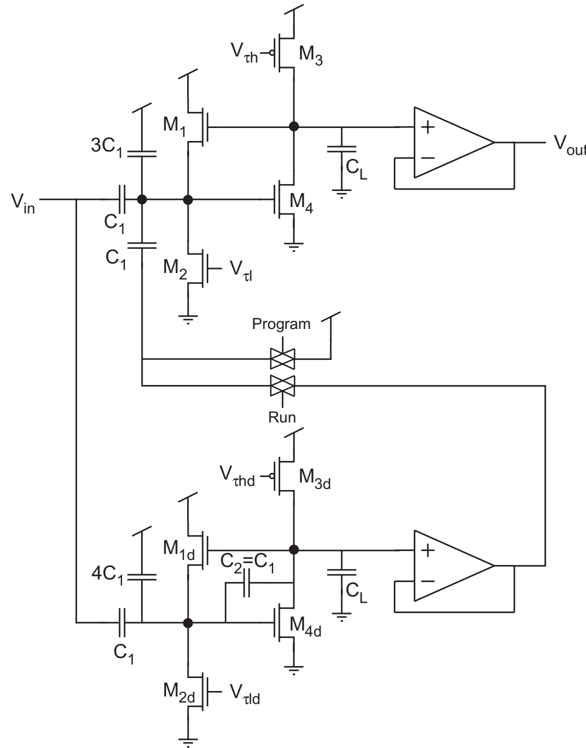

Fig. 5. Schematic of the effective circuit for each lateral-coupling filter tap. This schematic shows the C^4 of the representative filter tap and the dummy filter from the next higher-frequency stage. The main C^4 receives a capacitively coupled input from the dummy filter. The second input capacitor is connected to V_{dd} during programming, or tuning, mode so that it effectively adds to the total value of C_W, and the corner frequency will not change from tuning mode to run mode. In order to increase the Q and gain of the top C^4, the C_2 capacitor was removed.

of C_W; therefore, when the run-time phase is enabled, the effective capacitance seen by each time constant remains fixed, and the corner frequencies do not shift from programming mode to run mode.

Figure 6 shows the simulated and measured results of the lateral-coupling circuit. The narrowband and dummy filters were tuned using the discussion described in the previous section. Once the desired corner frequencies were set, the circuit was connected in lateral-coupling mode. Figure 6(a) shows the measurement and simulation data for each component of one filter tap, including the narrowband filter with no lateral coupling, the dummy filter, and the filter with lateral coupling. As can be seen, the laterally coupled C^4 has a much faster high-frequency roll-off than does the nominal C^4 (-40dB/decade as opposed to -20dB/decade). Also, the output of the dummy filter is clearly shown to be a wide bandwidth response, which simulates the effect of laterally coupling several of the higher-frequency stages.

Once the required relationship between the corner frequencies of the two C^4's was determined, the bias voltages were swept to emulate an array of laterally coupled filter taps (Fig. 6(b)). An exponential spacing of center frequencies (seen in the cochlea) was achieved by linearly sweeping the bias

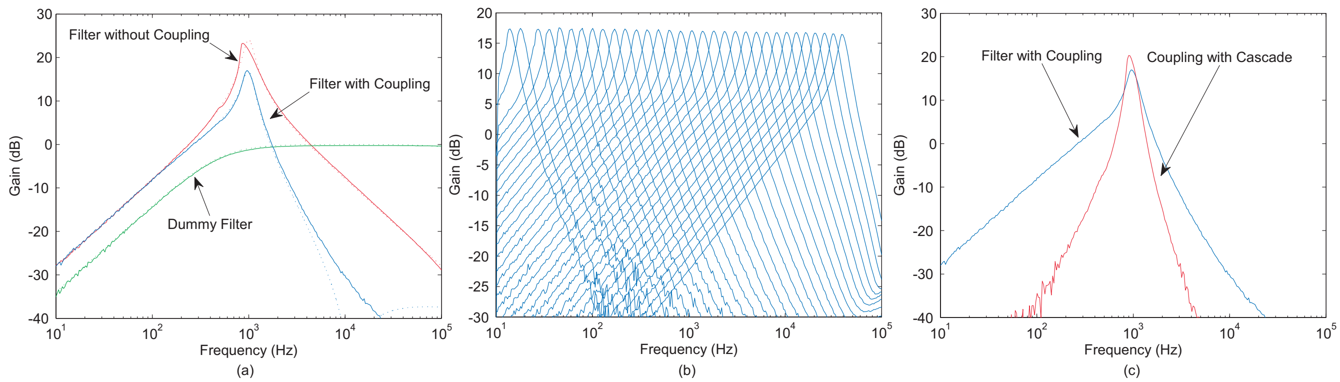

Fig. 6. (a) Individual frequency response for each filter in the lateral-coupling circuit as well as the frequency response for the entire filter tap. The center frequency is set to 1kHz. Simulation results are represented by dashed lines and actual data is represented by solid lines. (b) Frequency response measurements of the lateral coupling circuit. One filter tap was used and the bias voltages were swept linearly to change the center frequency for each frequency response curve. (c) Frequency sweep showing the relationship between a second-order lateral-coupling stage and a fourth-order lateral-coupling stage. The signal was attenuated after the output of the lateral-coupling circuit to remain in the linear range of the cascaded C^4. The slope of the fourth-order lateral-coupling stage is 20dB/decade steeper on each side, resulting in 40dB/decade going up and -60dB/decade going down.

voltages to get an exponential sweep of bias currents (subthreshold). An array of these filters could thus be fabricated to provide the same overall response.

Our final measurement cascaded the lateral coupling filter with a third C^4 tuned to the same frequency response of the narrowband filter. An attenuating circuit was used to keep the signal in the linear range of the cascaded C^4. Cascading the C^4's increased the order of the filter to yield a 40dB/decade slope going up and a -60dB/decade slope going down, as seen in Fig. 6(c).

VI. Conclusion

In this paper we have presented a novel silicon cochlear model which includes lateral coupling between filters to emulate the fluid coupling which occurs in the cochlea. Our lateral coupling circuit has a sharp asymmetrical frequency response reminiscent of auditory system tuning curves. This cochlear model is not subject to the same noise accumulation and phase mismatch issues seen in earlier cascaded models and is ideal for applications which require a more biologically accurate front-end for audio processing.

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