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Novel circuits for neural information processing

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Abstract

Information processing in the visual cortex of the mammalian brain allows compact image coding and representation. Receptive field structures found in the visual cortex of the mammalian brain resemble Gabor filters. There has been recent interest in the use of such receptive field profiles for image coding and texture processing. Systems employing such Gabor filters have been implemented in software for a variety of applications. We believe a hardware implementation of such cells will be helpful in artificial visual processing. We have implemented analog VLSI cells which perform such Gabor-like functions. We describe experimental results of our circuit. We have implemented both the sine and cosine type of circuits. The sine and cosine circuits described can be used as edge detection units and on–off center-surround units respectively. Our circuit is the first hardware implementation of a Gabor approximation circuit.

Keywords: Gabor filters; VLSI; Visual processing

1. Introduction

Neurons found in the primary visual cortex, i.e., the striate cortex, act as localized spatial frequency filters [1]. The receptive field profiles of such cells resemble even-symmetric or odd-symmetric Gabor filters [1]. There are two classes of orientation-selective cells found in the visual cortex [2]. Cells with two principal subregions, one excitatory and the other inhibitory, and cells with a central on or off region flanked on both sides by an antagonistic surround.

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The profile of the first class of cells resembles a localized sine wave and the second class a localized cosine wave both localized by a Gaussian-like profile. The first class of cells selectively respond to an edge and the second class responds to bar width. There are two schools of thought over the function of the visual cortical neurons. Some researchers believe that the visual cortical neurons act as feature detectors [3], while others believe that cortical neurons act as spatial filters [4, 5]. Each view has its own advantages and both views have very strong correlations. A nice argument in favor of feature detection is presented in [6].

Spatial frequency is defined as the change in the luminance as a function of distance. The receptive field structures found in the visual cortex are believed to act as localized spatial frequency filters. In a more mathematical approach they are believed to perform some sort of localized Fourier transform of the incoming signal. A frequency representation of a signal allows a sparser representation of the image than a feature representation [7]. From basic filter theory we know that a signal that is well localized in the time domain has a large frequency spectrum and vice-versa. Gabor [8] proved that a signal which is localized in time by a Gaussian window will have minimum number of components in the frequency domain. This is useful when one wants to perform some localized analysis such as a localized Fourier transform. Fourier analysis can be considered as the projection of the signal onto its set of basis vectors represented by sines and cosines of various frequencies and amplitudes. So a filter in the time domain which resembles a sine or cosine wave of a particular frequency localized by a Gaussian will have minimum joint uncertainty in the time and frequency domain. A series of filters tuned to different frequencies operating on the signal will give an optimal localized frequency representation of the signal. Such filters are known as Gabor filters. J. G. Daugmann [9] extended this principle to the spatial domain and also to two dimensions. In order to extend this form of patchwise Fourier analysis to two dimensional waveforms or patterns we must include the orientation of the pattern. These filters are called the 2D Gabor filters. 2D Gabor filters reduce the joint uncertainty in four dimensions. Gabor filters in two dimensional spatial domain is mathematically represented by a complex exponential grating localized by a bivariate Gaussian.

1.1. Spatial frequency versus spatial feature representation

The biological reasons for spatial frequency rather than feature representation is that there is a bottleneck between the optical system and the optic nerve [7] (roughly 130 million receptors to 1 million optic nerve fibers). Visual information is efficiently condensed when represented in the spatial frequency domain. This is also true for image processing systems, where the pixel by pixel representation generates a large amount of data which must be efficiently transferred through the communication system utilizing limited bandwidth. Another reason for utilizing spatial frequency representation is that the visual system needs to separate the relatively small luminance variations from the main illuminant. This could be easily accomplished by filtering out low spatial frequency components. Also the number of units needed to encode spatial frequency information is less since we could have units tuned to reasonably broad range of spatial frequencies. If the visual stimuli are spatially periodic then there is a clear advantage of spatial frequency filtering to feature detection, since the signal can be encoded by just its frequency, phase and orientation versus a lot of feature detection units. Even for relatively low spatial periodicities there is an advantage to using the frequency representation. Most objects in the visual world are spatially periodic [7]. Texture processing which is related to the phase information is easily accomplished using the frequency representation.

1.2. Localized versus global analysis

A localized analysis is helpful in identifying the slant and depth of textured visual objects [7]. A global Fourier transform would change its frequency spectrum for changes anywhere in the field. However, for many visual problems most areas remain unchanging therefore using a local analysis will allow the system to concentrate on the part of the visual world that is changing. Also visual information is locally periodic in space, and objects in the visual world are mostly spatially compact i.e., all the parts that make up the object tend to be adjacent to each other. These are powerful reasons to use local information processing for visual problems.

In the second section we describe our sine, cosine, and Gabor analog VLSI circuits. Finally, in the third section we summary our contribution.

2. Analog VLSI implementations

Our circuits model the receptive field profiles found in visual cortical neurons [10]. We have designed these circuits to respond to single points in space which in case of the logon circuits are represented as voltage pairs. We realize that a transformation from space to voltage is necessary.

2.1. Sine approximation circuit

The circuit implementation of a temporal sine wave is well known and is now considered trivial. The same argument does not hold for a sine wave with respect to an independent variable such as an input voltage. There have been two earlier implementations, one using BJTs [11] and the other using MOS transistors [12]. Both the implementations are similar and use the differential current representation. The normalized output results in a sine wave like profile. We have designed a sine approximation circuit. Our circuit closely follows the implementation given in [12].

We have designed the circuit taking many clues from biological systems. In experimentally derived response profiles of the cells in the visual cortex of the cat the sine profile is obtained by subtracting the response of the inhibition cells from the excitation cells [10]. The profile is equivalent to a Gaussian profile which is split at its center. Such a profile can be implemented in analog VLSI in a similar fashion. The generation of a Gaussian profile is done by using the circuit implementation of Delbrück [13] as shown in Fig. 1. The circuit is based on a simple current correlator shown in Fig. 2. For correlating transistors Delbrück defined a parameter S by:

$$S = \frac{(W/L)_{\text{middle}}}{(W/L)_{\text{outer}}} \tag{1}$$

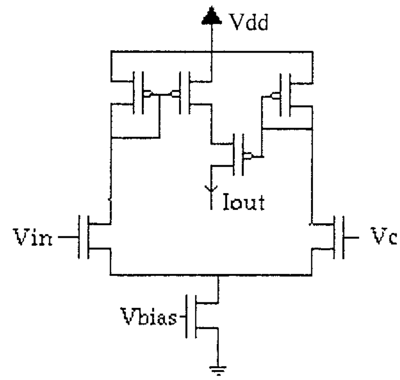

Fig. 1. The bump circuit of Delbrück.

Assuming the top transistor in the stack is in saturation (subthreshold), the output current of the current correlator can be computed as:

$$I_{out} = S\frac{I_1 I_2}{I_1 + I_2} \quad (2)$$

If the input currents to the current correlator are the limb currents of a differential amplifier then substituting this in the current correlator relationship provides:

$$I_{out} = I_b \frac{S}{4} \sec\ h^2\left(\frac{\kappa \Delta V}{2}\right). \quad (3)$$

This function gives a bell shaped curve which resembles a Gaussian. We have also reported a circuit that gives a Gaussian profile [14]. However, we will use Delbrück's circuit in the sine implementation because the design allows us to easily generate the sine-like profile. We use our circuit to achieve the Gabor logon profile discussed later.

The output of the circuit in Fig. 1 is fed as a bias current to a differential amplifier. If the input to the differential amplifier is similar to the input of the current correlator then the currents in each limb of the differential amplifier will resemble one half of a Gaussian wave. The input is given by mirroring the current in the input limbs to the limbs of the differential amplifier by means of an additional diode connected transistor as shown in Fig. 3. The circuit implements the following equation:

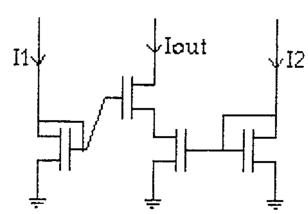

Fig. 2. The simple current correlator.

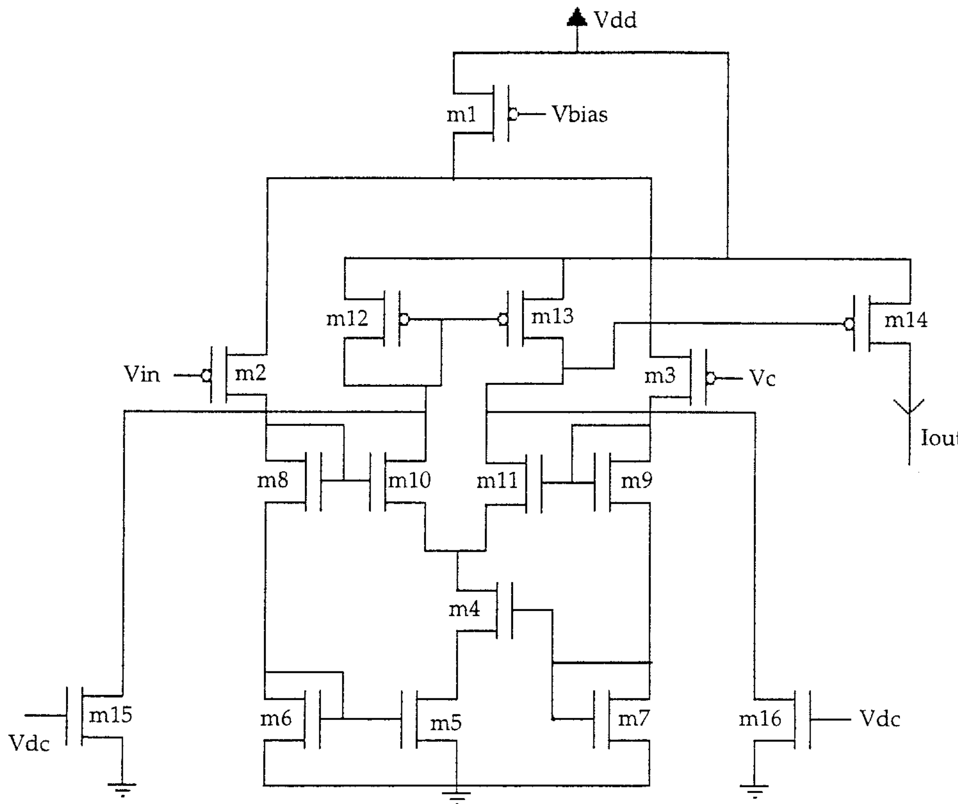

Fig. 3. The sine circuit.

$$I_{out} = I_b \ \sec\ h^2\left(\frac{\kappa \Delta V}{2}\right) \tanh(\kappa^2 \Delta V) + I_{dc} \tag{4}$$

where $\Delta V = V_1 - V_2$ and I_{dc} is the dc offset current.

The complete circuit diagram is shown in Fig. 3. Transistors m1–m7 form a PMOS version of the bump circuit discussed earlier. Vc determines the zero crossing of the sine circuit. Vbias is the bias voltage to the circuit. This bias must be sufficiently high in order to supply sufficient current to the diode connected transistors m6–m9. This is necessary to generate sufficient voltage levels to the tanh circuit formed by transistors m10–m13 because the sources of the differential pair transistors m10–m11 are not at ground potential but at some higher voltage.

The output from a fabricated chip is shown in Fig. 4. The chips were fabricated in 2μ *n*-well process using the MOSIS fabrication facility. The data was obtained using an oscilloscope with disk storage capability. The current from the chip was converted to a voltage by using a npn-BJT emitter follower off-chip. The data recorded from the oscilloscope was graphed using Matlab and Kaleidograph software. The effect of different biasing levels is shown. If the biasing level is slowly increased the bump output becomes more wide, quadratic, and then finally flat. For proper circuit operation the bias voltage needs to be at least a few hundred millivolts above threshold. Transistors m15–m16 set a dc offset to the circuit in order for the

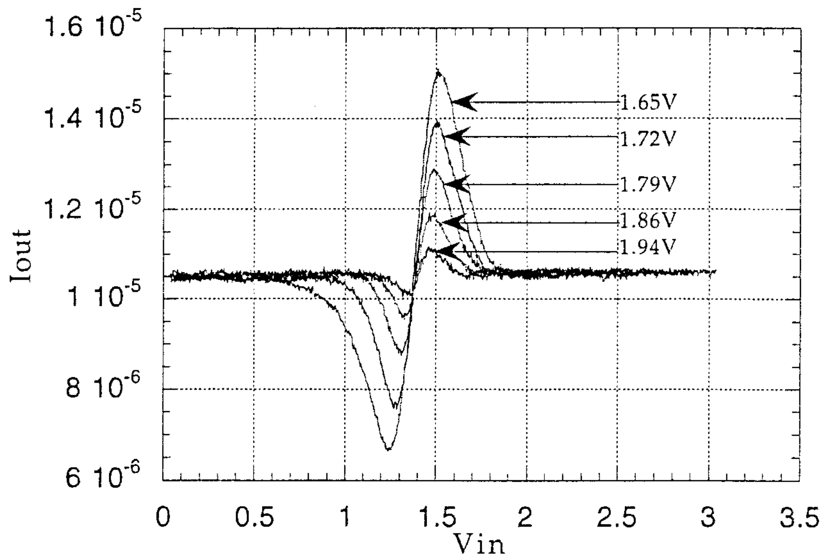

Fig. 4. The measured output currents for different bias voltages to the sine approximation circuit. Vc was held at 1.4 V.

circuit to be able to vary in the positive and negative direction. There is evidence in biology that there is a baseline firing rate corresponding to the dc level [15]. The input to these transistors are held at Vdd/2 for proper operation. Transistor m14 converts the voltage representation into a current representation.

2.2. Sine logon circuit

The sine logon is obtained by modulating a sine grating by a bivariate Gaussian. We, however, generate the sine logon profile by modulating the ouput of a edge detection unit by a Gaussian whose input is orthogonal to the input of the edge detection unit. Both profiles resemble each other. The circuit implementing the sine logon is shown in Fig. 5. The bias of the sine circuit shown in Fig. 3 is replaced by the Gaussian circuit presented in [14] and is shown in Fig. 6. The PMOS and NMOS transistors in series act as complementary current correlators. The drain connected PMOS load serves to keep the circuit in the subthreshold region of operation for a large part of the input and also facilitates the mirroring of the current. For symmetrical operation Vdd is kept at 3 V. A more detailed description is given in [14]. The advantage of using this circuit is it supplies higher current. The need for a higher current occurs because the diode connected transistors m7 and m8 need a sufficient input current to generate voltage ranges which allow the differential amplifier to operate properly. Another advantage is that this circuit can be easily made multi-dimensional as shown in [14]. This allows the input to be a complex feature such as lines. We however show results only from the simple implementation. The bias current effectively controls the amplitude of the sine wave and when modulated by a Gaussian bias current results in a sine logon-like profile. The measured output current from this circuit is shown in Fig. 7.

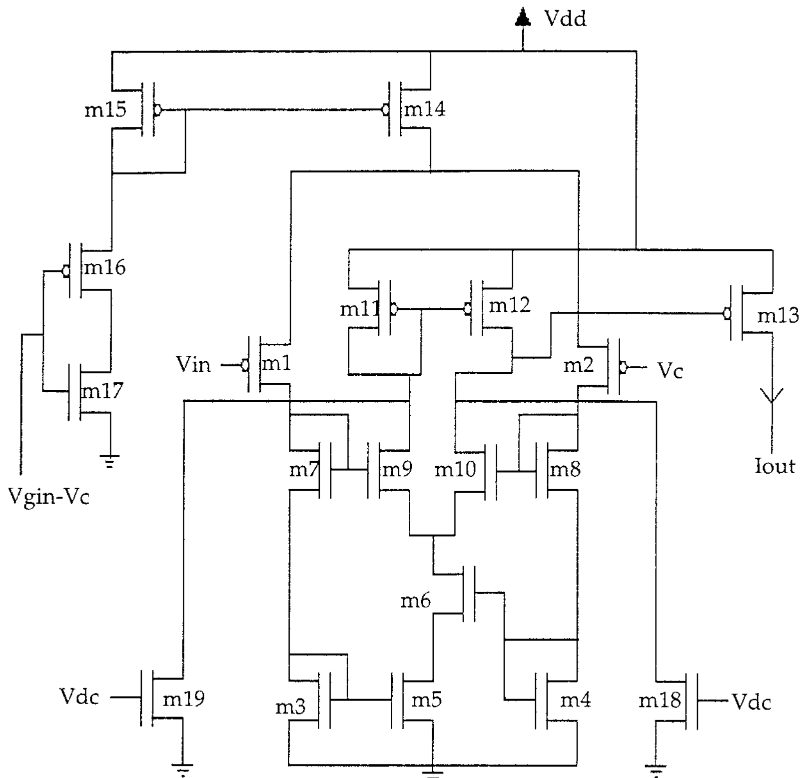

Fig. 5. The sine logon approximation circuit.

2.3. Cosine approximation circuit

Our cosine approximation circuit implements an on-center off-surround profile which resembles a Gaussian localized cosine wave. A circuit for generating a cosine wave using BJTs is given in [11]. We, however, use our own implementation using MOS transistors. Our implementation uses a fewer number of transistors.

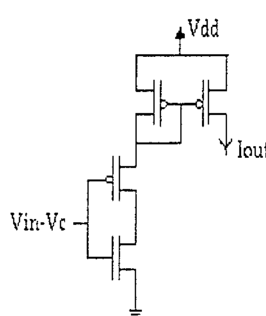

Fig. 6. Our Gaussian cell.

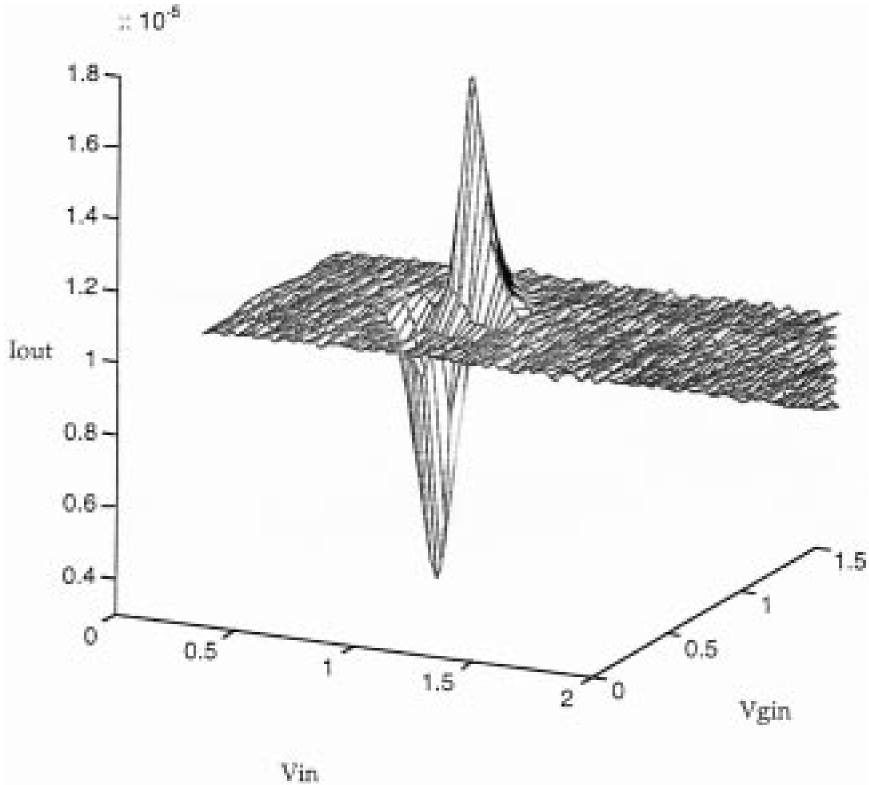

Fig. 7. The measured output of the sine logon circuit.

Our circuit is shown in Fig. 8. Transistors m1–m7 implement the bump circuit discussed earlier. The output of the bump circuit is fed as a bias current to the differential amplifier. Also the bump circuit output is fed as an input to the differential amplifier. If the other input to the differential amplifier is a voltage that lies near the tail of the bump circuit then a cosine like output results. Since we do not known this voltage a priori a simple bias will not suffice. We now consider the design of such a bias. Intuitively we know that the peak current occurs when the input to the differential amplifier are equal. Thus if we duplicate this circuit and keeping the inputs equal to the center voltage we can obtain a current that is equal to the current at the peak. But we need the current to be slightly smaller, therefore we have to make the S ratio of the bias circuit slightly smaller than the S ratio of the bump circuit. We used S ratios of 0.5 for the bump circuit and 0.48 for the bias circuit. This ratio is calculated assuming equal currents in both limbs to simplify the calculation. This elaborate bias is done to provide robustness to fabrication parameters. Transistors m8–m14 forms the bias circuit, m15, m16, m20 and m21 are the diode connected mirroring transistors. Transistors m17–m19 and m22–m23 form the differential amplifier, m24 converts the voltage to current representation. Transistors m25–m26 forms the dc current bias to the circuit. The measured output of this

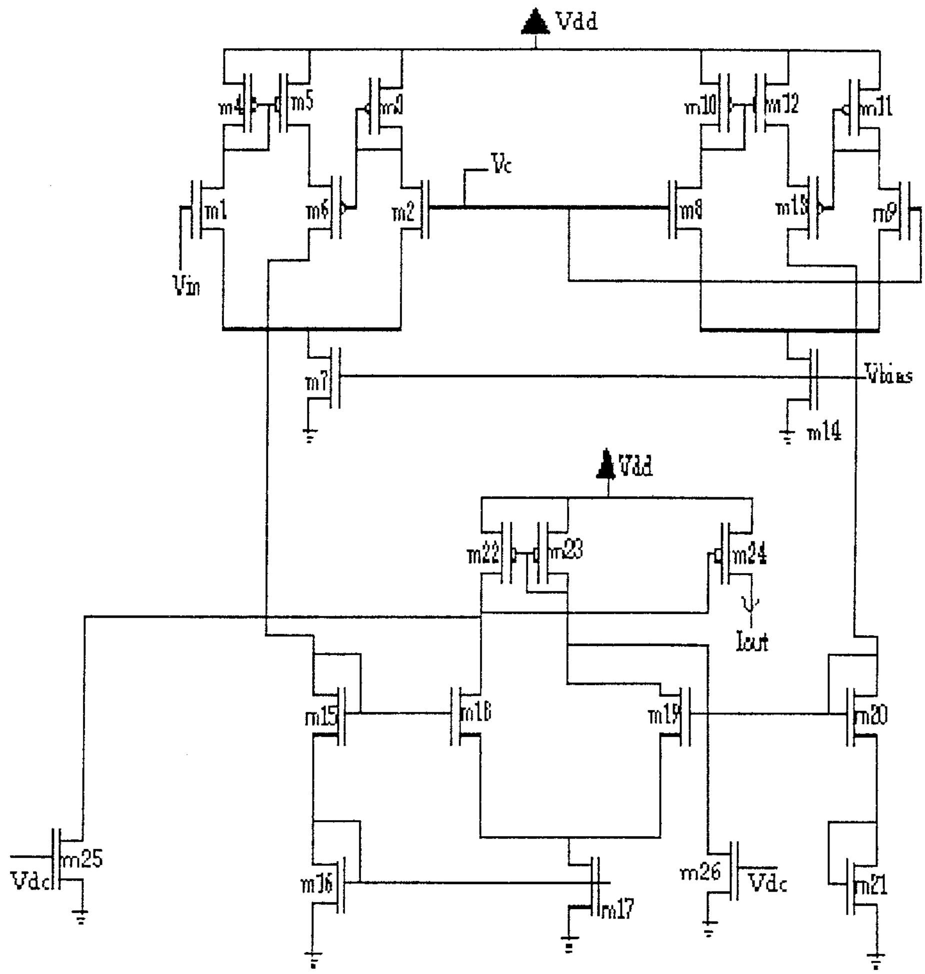

Fig. 8. The cosine approximation circuit.

circuit is shown in Fig. 9. The transistor sizes for the cosine approximation circuit are shown in Table 1.

2.4. Cosine logon circuit

The cosine logon is designed using the same design philosophy as the sine logon circuit. The complete circuit is shown in Fig. 10. The measured output of the circuit is shown in Fig. 11.

In addition to the above described functioning of these circuits, we can change the output waveform by changing the voltage on the Vdc inputs. If Vdc is below Vdd/2 then the negative or off lobe of the output is decreased and the positive lobe dominates. If Vdc is greater than Vdd/2 then the negative lobe will dominate. There are many receptive fields with asymmetric lobes in the visual cortex of the cat [10]. Our circuit can be used to model a variety of receptive

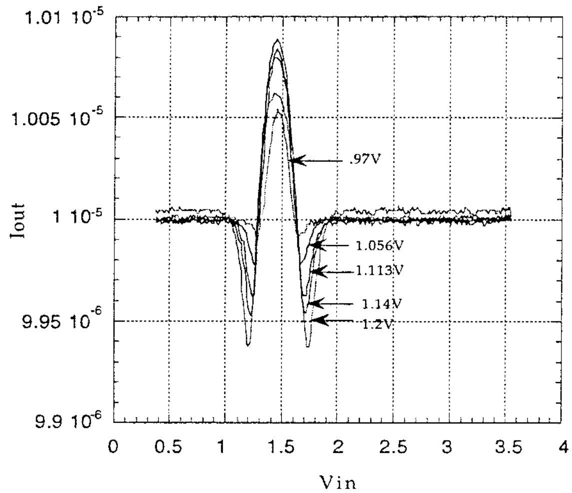

Fig. 9. The measured output of the cosine circuit.

field by effectively controlling the Vdc input. We can also obtain profiles that are inverted to the ones shown in Figs. 4 and 9. This can be done by subtracting the limb currents in an opposite fashion to the ones shown in Figs. 3 and 8.

3. Conclusion

Visual cortical neurons perform both as localized spatial frequency filters and simple feature detectors. We have presented compact analog VLSI circuits which perform similar operations. We believe that such cells will be very useful in artificial visual processing. The cells presented may be used as Gabor filters or as simple on-center off-surround cells. The cosine circuit may be additionally used as the Mexican hat activation function in neural networks.

Table 1
Transistor sizes for the cosine approximation circuit

Transistor	W/L
M1–M12	3/2
M13	7/5
M14–M23	3/2
M24	4/2
M25, M26	3/2

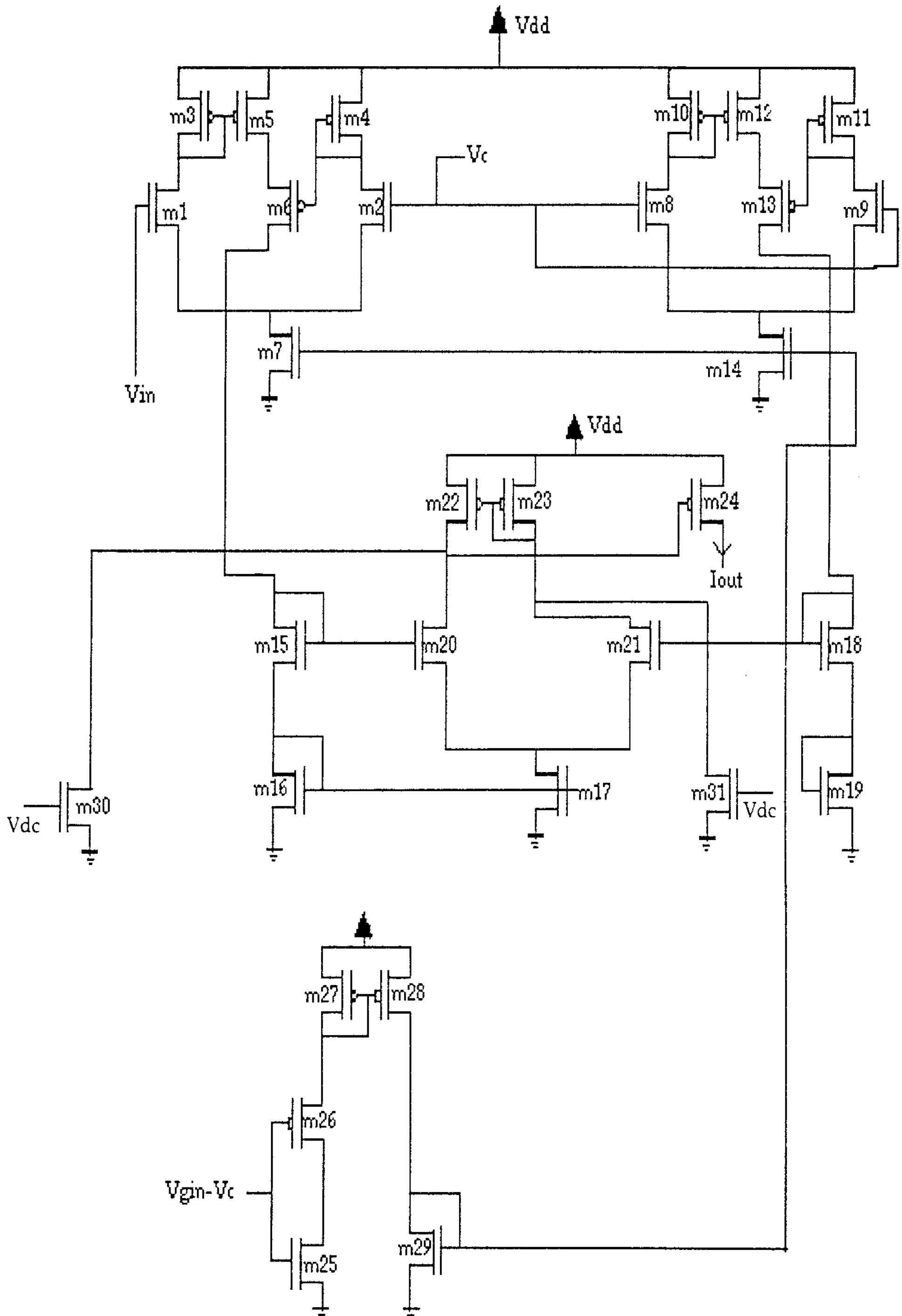

Fig. 10. The cosine logon approximation circuit.

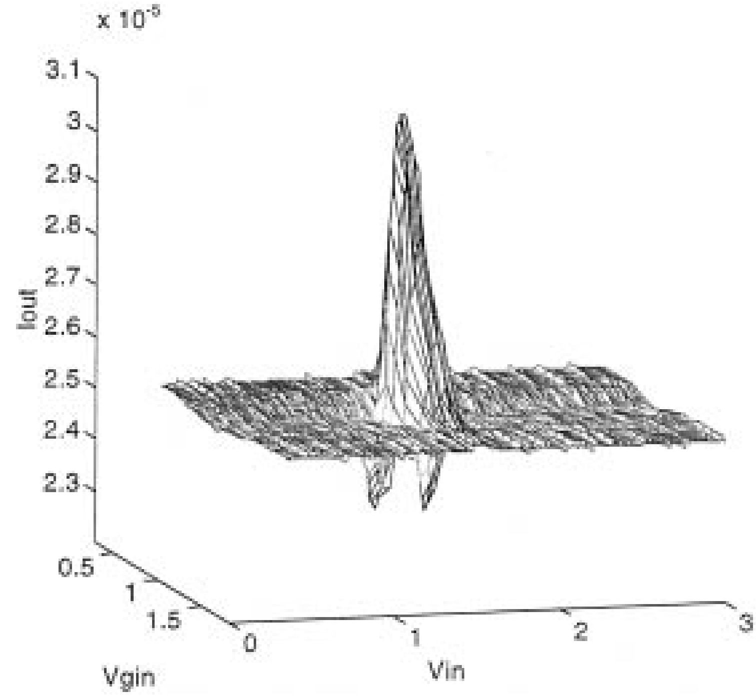

Fig. 11. The measured output of the cosine logon circuit.

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