Matrix Multiplier - An Analog Approach

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ABSTRACT

Keywords: Matrix, Analog, Multiplier, Squaring Circuit, Operational Amplifier, Analog Computer

Our project presents an alternative approach in doing matrix multiplications. As of now, matrix multiplication or most of the numerical calculations are done by digital computers. Digital computers takes a noticeable time when calculating large volume numerical calculations. But in our analog electronics based approach, the computation time could be reduced drastically.

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Chapter 1

Introduction

1.1 Overview

Matrix Algebra is a very useful tool for any Science or Engineering field. We often express a system, its state, its configuration in terms of various matrices. And to analyze its state, its behavior, its interaction with other system, we often need to perform various numeric operations on those matrices. This numerical manipulations are mostly done by digital computers. And as we already know that the digital computers work on the principle of two states - HIGH '1' and LOW '0'. This limits the scope of mathematical computation in terms of time complexity. In comparison between CPUs, GPUs and Digital ASICs, ASICs may perform better than CPU and GPU but still it utilizes many clock cycles for various operations other than numeric calculation. So, In this regard, we want to propose a different approach in doing numeric calculations in matrices, especially Matrix Multiplication. This approach can reduce the computation time drastically.

1.2 Problem Formulation

Let's say we have two 2×2 matrix and we want to multiply this.

$$A = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \text{ And, } B = \begin{bmatrix} p & q \\ r & s \end{bmatrix}$$

$$\text{Now, } A \times B = \begin{bmatrix} ap + br & aq + bs \\ cp + dr & cq + cs \end{bmatrix}$$

So, we can see that the simple 2×2 matrix multiplication results in 8 different numeric multiplication and 4 distinct addition.

To generalize this, a $n \times n$ square matrix multiplied by another $n \times n$ square matrix will result in n^3 multiplications and $n^2(n-1)$ additions.

In case of 8051 microcontroller, a single multiplication event consisting of MOV and MUL instruction requires a total of 60 T-states (12 T-States for MOV[1] and 48 T-states for MUL[1]). So, for a 100×100 matrix multiplication, this requires few thousands of T-states leading to a noticeable time delay.

1.3 Objective

As per our project topic, our main objective is to sketch a Analog Circuitry, which can multiply two numbers and then using those multiplying cell to produce an output equivalent to matrix multiplication.

1.4 Motivation

In every domain of Science and Engineering matrix is there. For low volume numerical computations, digital computers are fine but in case for very large volume of numerical computations, digital computers are not suitable. And in our Industry 4.0 era, we need real time processing of physical variables. This is totally unsuitable digital computers. So, we tried to find an alternative solution to this problem and realized that an analog computer specialized in doing matrix multiplications would solve those issues.

Chapter 2

Background

2.1 Review of Literature

Matrix multiplication using methods other than digital computers dates back to 1970, when RA Heinz, JO Artman, SH Lee were trying to develop a mechanism for matrix multiplication using Optical Methods. It comes to 1990 when F.J. Kub; K.K. Moon; I.A. Mack; F.M. Long tired their approach to design a matrix multiplication using MOSFETs. What we've tried to do is to develop a matrix multiplication system using Op-Amp. We've exploited the characteristics of class AB output stage of BJT based OpAmp. This phenomenon was first showed by, Surakamontorn Wanlop in 1988. Later Surakamontorn Wanlop, Vanchi Riewruja and many others exploited the same technique to produce various Squaring Circuits.

2.2 Methodology

We've already defined our Problem Statement. Now to solve those issues by designing another approach to matrix multiplication, we've taken the following steps.

1. Using a DAC, we'll convert the numbers from digital format to analog voltage level.
2. Using an analog multiplication cell, we'll multiply the numbers.
3. Using an analog voltage adder, we'll add the desired multiplications.
4. Using an voltage scaling device (variable gain amplifier), we'll remove any distorting due to up-scaling or down-scaling.
5. Using an ADC, we'll convert the final output to digital format.

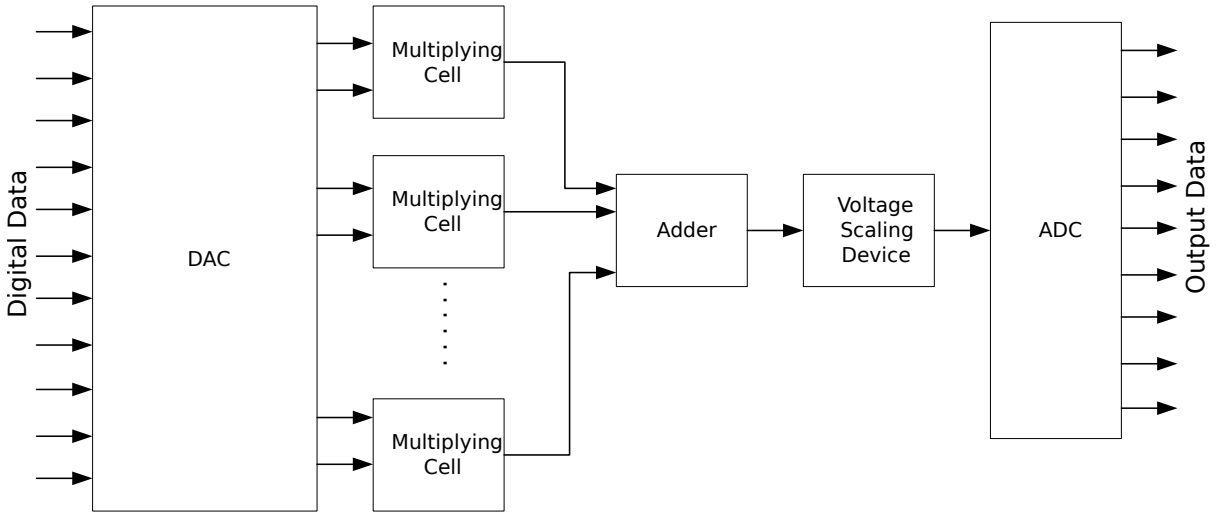

Figure 2.1: Overall Procedure

2.3 Procedure

We can use $n \times n$ distinct multiplication cell for the fastest operation. We can share a single multiplication block for different rows and columns. Or we can use a hybrid form of these, where we can use a few number of multiplication cells and then sharing them for different rows and columns.

We can also take the same approach for DAC and ADC.

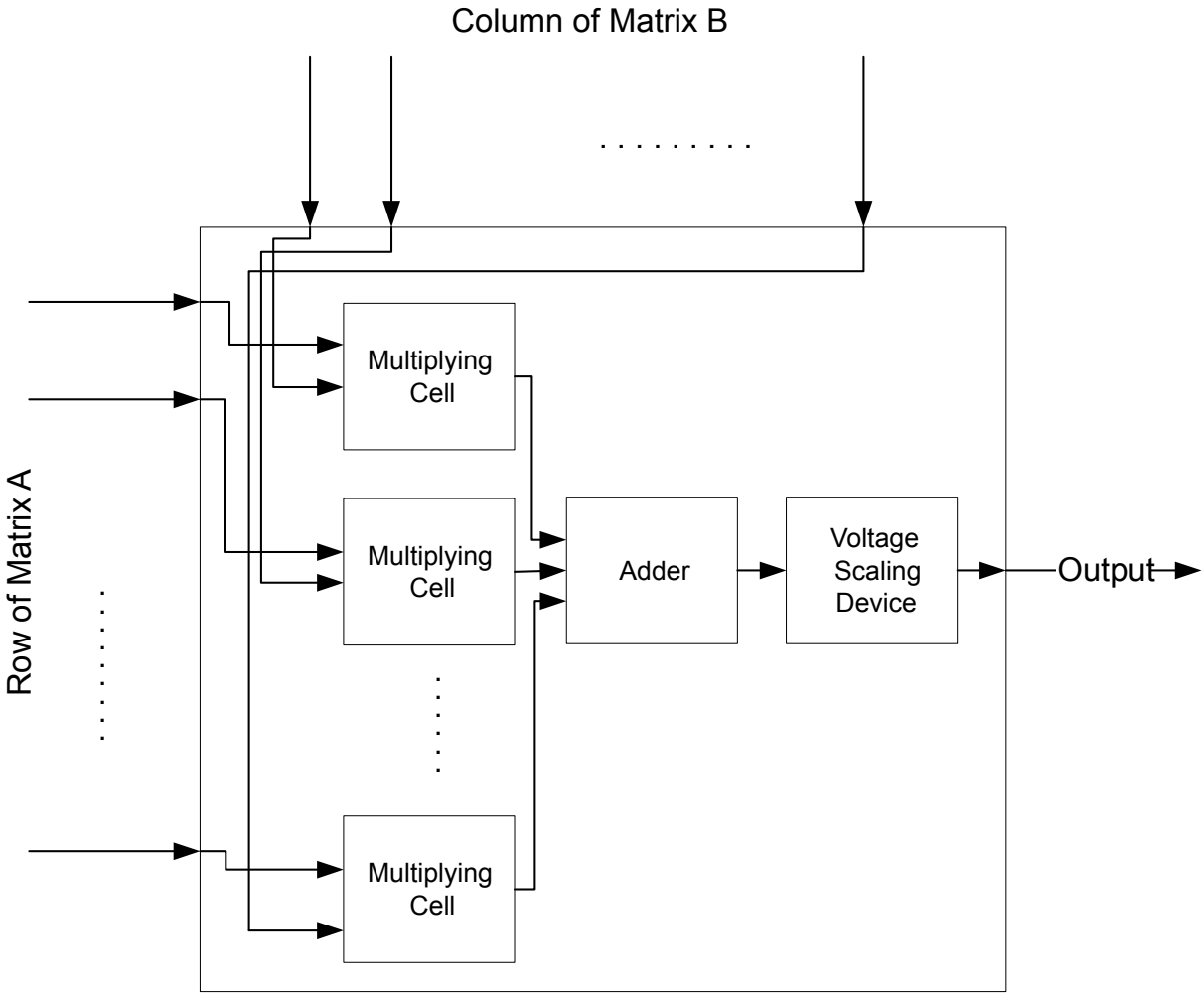

Figure 2.2: Overall Procedure

Chapter 3

Circuit Description

3.1 Multiplier Cell

3.1.1 Generating $(V_1 + V_2)$ and $(V_1 - V_2)$.

V_1 and V_2 input voltages are added and subtracted to have the $(V_1 + V_2)$ and $(V_1 - V_2)$ voltage outputs.

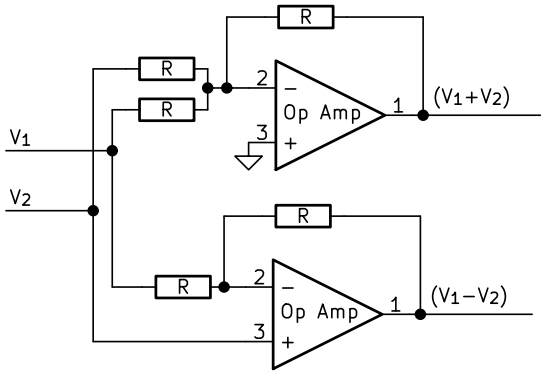

Figure 3.1: Producing $(V_1 + V_2)$ and $(V_1 - V_2)$.

3.1.2 Squaring Circuit

Now the $(V_1 + V_2)$ and $(V_1 - V_2)$ outputs are squared using two different squaring circuit and we get $(V_1 + V_2)^2$ and $(V_1 - V_2)^2$.

There are many squaring circuit schemes. All of them exploited the class AB output characteristics of an Operational Amplifier. We decided to go with the schematics presented by Wandee Petchmaneelumka, Kiettiwan Songsataya, Vanchai Riewruja, and Prasit Julsereewong in their paper presented at ICCAS 2005[4].

This squaring circuit in figure 3.2 will produce an output $V_{out} = KV_{in}^2$ [4] where K is some constant depending upon the various resistors connected to the operational amplifiers.

So we can use this squaring circuit to product $(V_1 + V_2)^2$ and $(V_1 - V_2)^2$

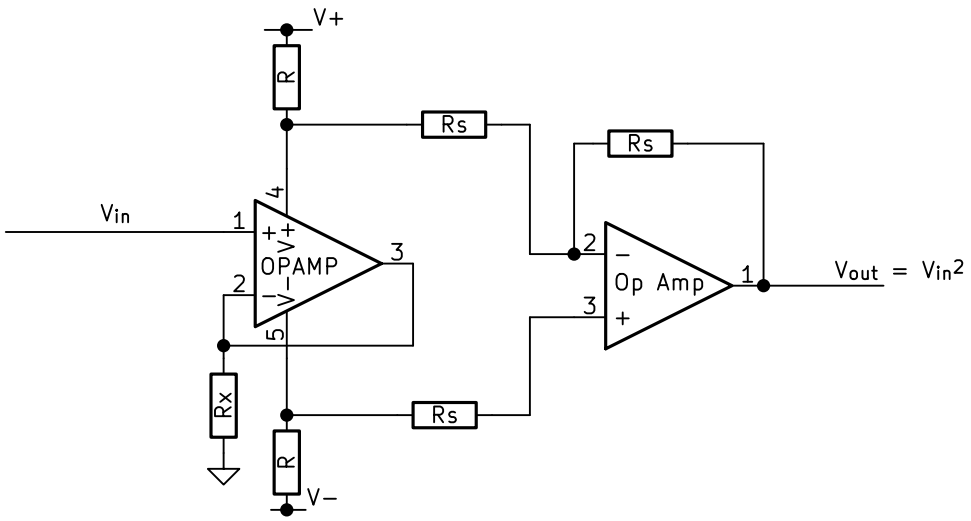

Figure 3.2: Squaring Circuit.

3.1.3 Generating V_1V_2

Now the $(V_1 + V_2)^2$ and $(V_1 - V_2)^2$ outputs are subtracted using subtraction circuit to form $4V_1V_2$. And then we can down-scale this using a amplifier of gain $\frac{1}{4}$ and we now have the perfect V_1V_2 output.

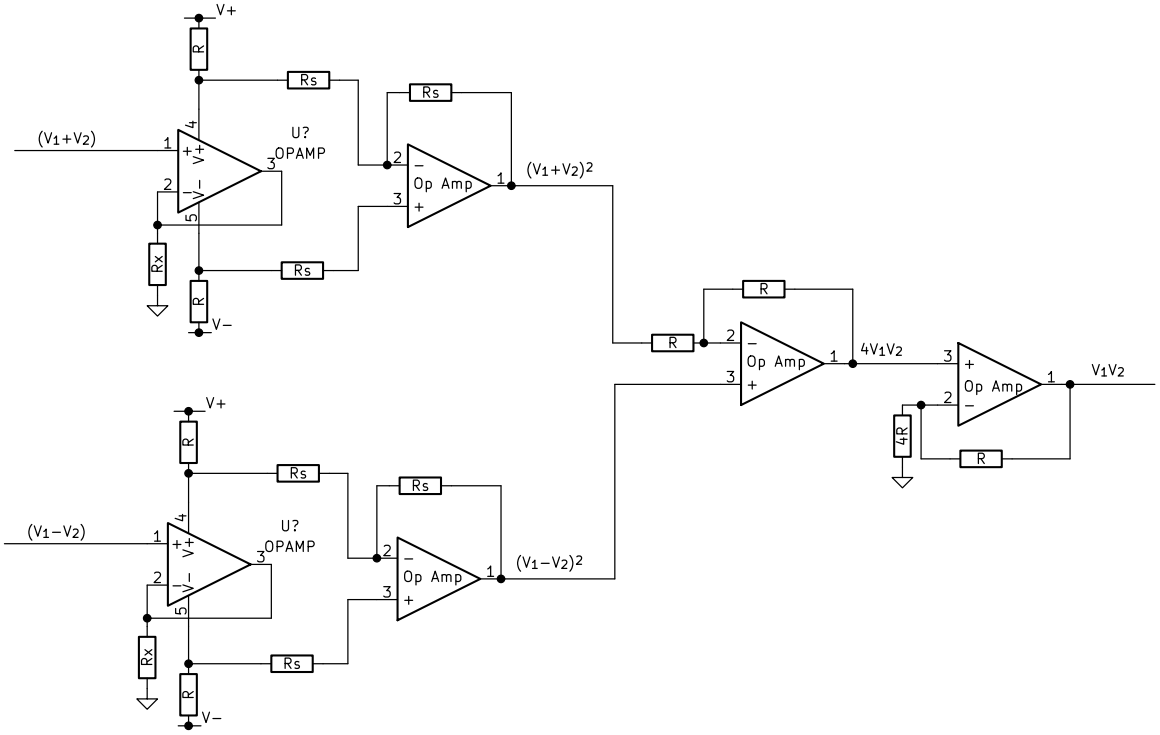

Figure 3.3: Generating V_1V_2

3.2 Adder Circuit

This Adder Circuit will perform the arithmetic equivalent of addition of the various product-terms in each cell of the resulting matrix.

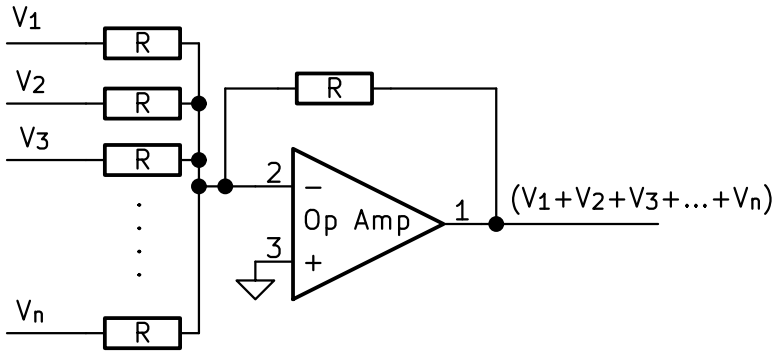

Figure 3.4: Addition of product-terms.

Chapter 4

Experiments and Result

4.1 Multiplier Block: Squaring Block Test Schematics

At first we've tested the performance of the Squaring Block.

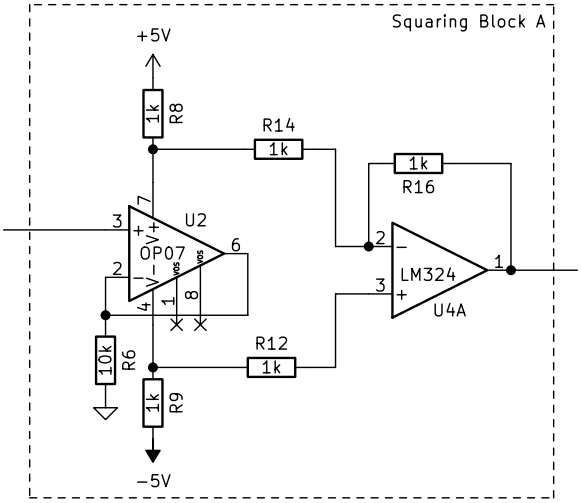

Figure 4.1: Multiplier Block

We have measured the DC Transfer characteristics. The results are listed below.

Observation	Input Voltage (V_{in}) (mV)	Output Voltage (V_{out}) (mV)
1	508	237
2	598	276
3	682	313
4	760	349
5	837	379
6	915	413
7	985	449

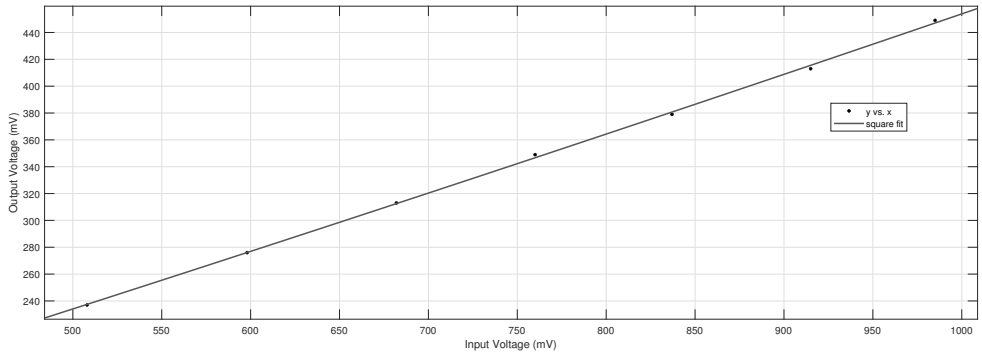

Figure 4.2: DC Transfer Characteristics.

4.2 Multiplier Block: Full Test Schematics

This is the exact circuit which we used to test our prototype.

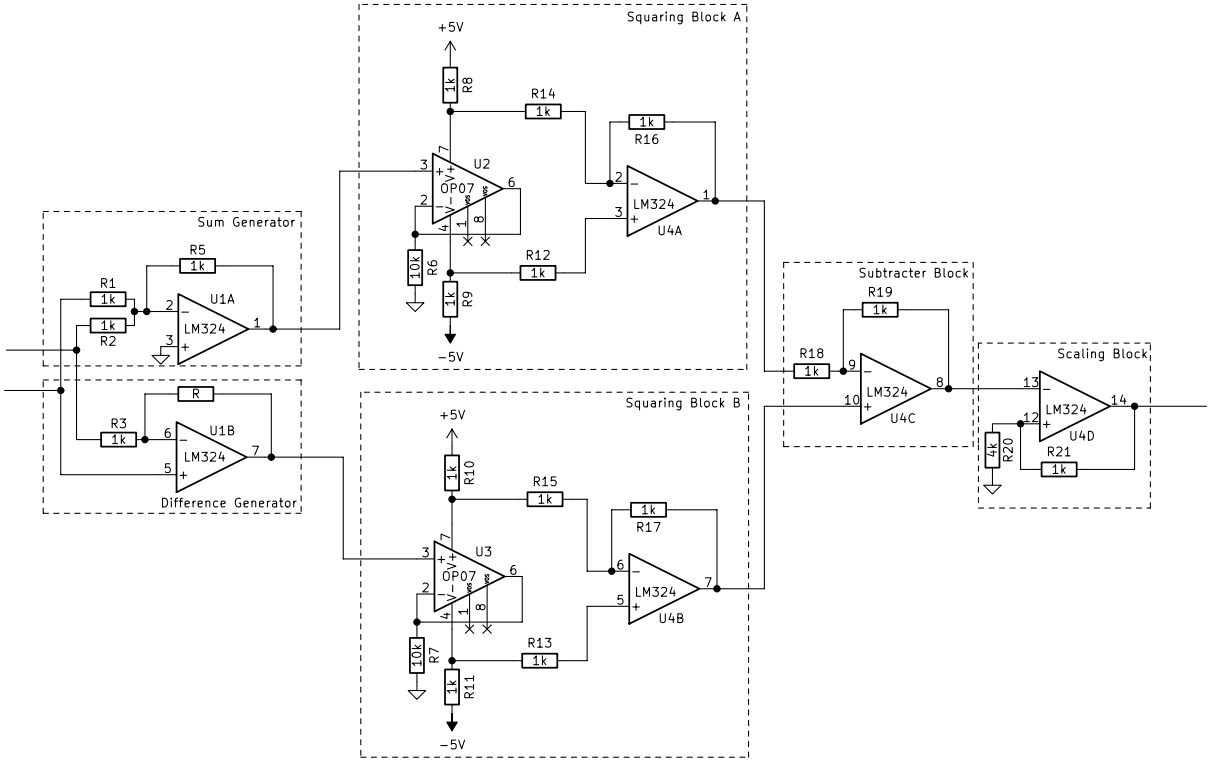

Figure 4.3: Multiplier Block

4.3 Matrix Multiplication (Partial): Full Test Schematics

For a prototype, we chose a 2×2 matrix multiplication and computed only the element of the first-row-first-column.

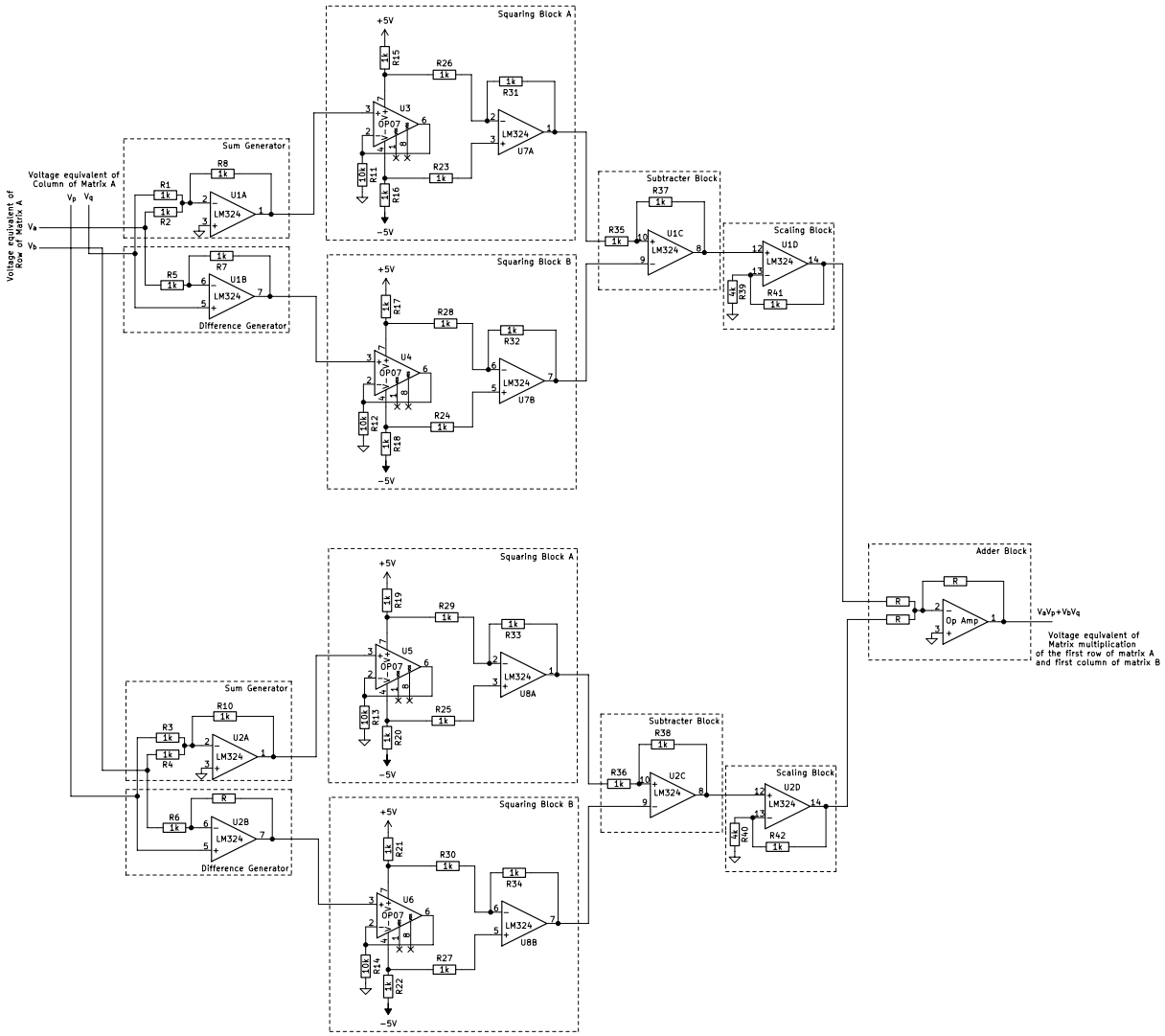

Figure 4.4: Generating output of the first cell of resulting matrix.

Chapter 5

Observations and Conclusion

So what we have observed is that the circuit behaves as it should. But component tolerance and device matching is a key factor in getting a undistorted output. We have also observed that the input voltage range is quite limited for the desired behavior. So we'll have to use a very high resolution and ultra-low noise DAC. It was expected that due t to environmental conditions and natural variability, the result from this approach will have some error in its output. So this approach is not suitable for precise and accurate numerical calculations. This is more suitable for those applications where the precision is not so important.

So from our observations, we may conclude that the this approach of doing matrix multiplication could be an alternative to the digital computation.

Chapter 6

Future Scopes

This approach could find its way to every scientific applications because of its real-time numerical ability. In particular AI/ML is a great area for the application of this technique. Real-time object detection, speach recognition could be useful for the differently-able persons. This can also help to take instant decisions based on objective measures and could thousands of lives.

In addition to this, a full fledged Analog Processing Unit which can do other mathematical calculations than just matrix multiplication such as solving partial differential equations could revolutionize the numerical methods and computational power.

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