Bachelor Thesis

Electromagnetic Energy Harvesting in 28nm FD-SOI technology

Bachelor thesis

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submitted by

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The Institut de Microélectronique Electromagnétisme et Photonique and LAboratoire d'Hyperfréquences et de Caractérisation, IMEP-LaHC, is a “ unité mixte de recherche (CNRS/Grenoble INP/UJF/Université de Savoie) ” of 150 people strongly committed in research activities related to micro- and nano-electronics, microphotonics, micro- and nano-systems, microwaves and microwave-photonics.

The laboratory is settled over two sites : Grenoble-Minatec (38) and Le Bourget du Lac (73).

Research activities of IMEP-LaHC cover large areas (materials, technologies, components, circuits and systems) which allow carrying out multidisciplinary research in common with our partners in nanophysics, material chemistry, circuit designers or system manufacturers in electronics and optoelectronics.

Situated at convergence of many sciences and technologies, IMEP-LaHC can play an important federating role to develop ambitious projects and to challenge the future of electronics.

Such activities are regrouped in 3 research themes with potential applications (semiconductors, informatics, telecommunications,) representing important goals for economy of next decades.

I was in the RF group during my training period.

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1 Introduction

1.1 Aim

Energy consumption is gradually increasing and it does not seem that to stop doing it so. This is the reason why, with the ambition of doing a part to satisfy our planet needs here I introduce a proposal in order not to let energy go to waste but instead to be capable of recovering part of it.

The main purpose of this memory is to present a viable solution for RF energy harvesting. We need to begin to introduce new ways of conceiving the use of energy if we want to continue living the way we do now. This implies not only finding a good solution but also an easy to implement, relatively economic and plausible one.

This memory includes solutions to the needs and problems that have appeared during the project always taking into account the major goal and searching for the most optimal solution.

Finally, what this proposal also intends, is to generate an interest in this new vision of energy and for the world to start seeing this kind of energy sources as a possibility to become a more efficient and environmentally friendly society. Not only because it is beneficial to our economy as prices of fossil fuels are going up but also because we are running out of resources.

1.2 Purpose

The main purpose of this project is to generate energy by considering electromagnetic waves that are floating in the air as a possible energy source or more accurately, as a way of recovering this energy. In order to accomplish that different circuits are simulated and the component's values are established so we are able to transform them into profitable energy given the restrictions and in the best of the conditions.

1.3 Range

This proposal will include a possible solution for recovering energy from an antenna. In this matter, it includes various circuits which together could reach this goal. However, it does not comprise the details of how these waves are received and transformed into continuous energy.

On the contrary, it will explain how this continuous signal is treated so it can oscillate only by recovering these waves. Furthermore, it will also enclose the way in which a greater power is obtained from such a weak source so it can be actually useful. The steps that had been followed as well as all the difficulties that have been encountered when searching for effective results will be defined during the report. Also, a profound analysis of different options must be made so the most convenient and optimised solution can be reached.

Finally, it must be mentioned that this report will only include the simulation of the circuit and its results. This means that the layout and the subsequent construction is left for future development.

2 Objective of this report

- Pose a solution to the initial problem: how to recover energy from electromagnetic waves?
- Calculate and define the values of the various components of the circuits required in order to accomplish a useful output.
- Study various possible alternatives and establish which judgements will be crucial when deciding the best option.
- Develop the best solution and determine its future development.

3 Actual situation

3.1 Conflict

We live in a world that is constantly changing. Only a few years ago recycling was not even a word while nowadays there is practically no field where recycling is not present. People might feel different or have different opinions about how recycling must be done or how far we should take it but what we cannot deny is that by recycling we are in some way doing the right thing. Since the industrial revolution we have not stopped to pollute our world and it is a fact that there have been dangerous consequences: holes in the ozone layer, the continuing raise of the average temperature etc. These caused a revolution of thinking and a change of the ideals that were dominant back then. People started caring about the planet, they became aware of how much damage they have done to it and Scientifics started looking up for the causes of these dreadful circumstances. Agreements between countries were signed, restricted deforestation laws were established, separated bins were placed, CFC's were forbidden and non contaminating transport was promoted. And all of this was only the beginning of a raising awareness and an out bursting interest to begin the protection of our birthplace. All these new movements resulted in the actual concern about environment. In this frame is where the recuperation of the electromagnetic energy is placed. Although it may seem a quite different matter at the end it is only a more abstract way of caring about our world but it is still a way of doing it.

Imagine for a while a world without energy power, would you be able to live in it? Are you aware of how many things you will have to give up? It would be a great step backwards and a complete destruction of the world we know. Energy is so present in our lives and it has enabled us to make such important discoveries that it must be given the importance it deserves. It is a crucial part of our lives.

That is why this kind of project first caught my attention. I believe that in order to continue our lifestyle we must start to take this matter seriously and start doing little things in order to amend all the destruction we have caused over the years. It is only in our best interests to help heal the earth.

Once the basic conflict has been established it is time to focus on the recuperation of electromagnetic energy.

When we talk about recycling we are referring to use something that is going to be wasted another time, in other words, to reuse. This concept has been applied to many things such as trash, water, soil… The great idea about the recuperation of energy is to transport this concept to technologies. When using a mobile phone, internet, and television we are exchanging information by electromagnetic waves, tones of them. In fact we are surrounded by a whole mass of waves that are initially sent in all directions by a first antenna. So why waste the vast majority of them if we could somehow extract some benefit?

This is what this project is about, to take advantage of an existing energy that is going to waste and make the most of it. The idea is simple; however there are many factors to take into consideration. The goal is to capture waves with an antenna and attach a circuit which increases the input voltage up to a point where it can be used as an energy source. This way we would be using an initially wasted energy instead of having to create it with a battery.

3.2 Study of the needs of the users and needs that will be covered by the project

As it has already been mentioned our society needs a change because in a not so far away future it will not be possible to continue using fossil fuels the way we do now. This is why the main need this project expects to cover is a step towards a new perspective in energy consumption. It is about making a real proposal which brings us closer to a cleaner world. This is a global need which will not only be beneficial to the consumers of the product but also to all society in general.

Furthermore, this proposal has to be useful and comfortable for different kinds of users. For this reason this circuit should be implemented in a small and light device. It should be capable of catching as many frequencies as possible, thus users can take advantage of this technology no matter the external use. This project will not cover the design of the layout neither the outside cover. However, this fact will definitely be taken into account when trying to minimize the size of the different components of the circuit.

Finally, it is in everyone's best interest to create an efficient device whose cost is as low as possible. Construction of the device will not be studied in this project and consequently costs will not be specified but in a further study different materials and methods of construction should be compared in order to accomplish a low cost.

3.3 Location and geographical conditions of the project

When deciding where does this project applies to we could say almost anywhere. Almost anywhere because the major condition which needs to be fulfilled is that there exist waves around the device.

However, there are some conditions that raise the possibilities of success of the circuit and location may be one of them. For example, if we were to be in Africa there would be fewer waves than let's say the centre of Europe and this will reduce the amount of energy we can recover and consequently a misuse of this device. Indeed, not only do we need to consider the geographical location, but the local one too. By this I mean placing the device inside or outside a building as the power attached to each frequency band is different. For example, if we are talking about wifi, it is clearly more efficient inside buildings while mobile phone's frequency works better outdoors. This is why when choosing the location of this kind of devices we must take into consideration the amount of waves that surround it as it can be a major cause of failure.

What will also be interesting to establish is whether there is some waves which work better that other ones. By this I mean if some frequencies are more likely to produce energy than others. The aim is to be able to choose which frequency we would like to work with but if this is not a possibility, a compromise between choosing the frequency that works better and the one we can make our circuit work with must be done.

Furthermore, the perfect location should be one without interference. As this is impossible what we should try is to find a location with very few of them. This can be kind of contradictory with the previous point because the location where there are more waves is usually the one with more interference too. What should be done in such case is to try to minimize the effect of them in the device.

Also, a place where weather does not highly affect the proper working of the device should be found. However, it is true that weather interference is indeed unavoidable.

Finally, when choosing the perfect location we must also bear in mind the demanding market. It goes without saying that even if there is an area where the perfect conditions exist but no one is interested in this product on it, there is no point in bringing it there. Thus, we must learn which the potential clients of the device are so we could focus on where they are placed and which are their needs and demands.

4 Description of precedents

Energy harvesting is a trendy topic currently. Many people are studying the different possibilities of saving up energy and therefore, recovering some of that which may be wasted is a way of doing it. Thus, energy harvesting is a key technology for enabling a long-term, maintenance-free operation of low power electronic devices.

It must be said that there are different types of energy harvesting but the one that is concerning us is energy from RF transmitters. This energy can provide unique benefits including predictable and consistent power over distance, and enable the energy harvester to be untethered from the power source. This is one of the reasons why in one way or another people has been doing research on this area trying to come up with different and useful solutions.

In order to put some practical examples we could talk about an energy-harvesting device capable of utilizing the signals from a wide variety of energy sources -such as microwaves, Wi-Fi signals, satellite signals, and sound signals- which has been created by researchers at Duke University's Pratt School of Engineering [1]. This new device has achieved an energy conversion efficiency of up to 37%, putting it on par in that regard with solar cell technology. It works on a similar principle to that used in solar panels, but in this case the energy involved isn't light energy, it is other forms of wave energy. The key to the device's impressive abilities apparently lies in its application of metamaterials which are, essentially, simply engineered structures that are able to capture various forms of wave energy and tune them for useful applications. Concretely, they used a series of five fiberglass and copper energy conductors wired together on a circuit board to convert microwaves into 7.3V of electrical energy.

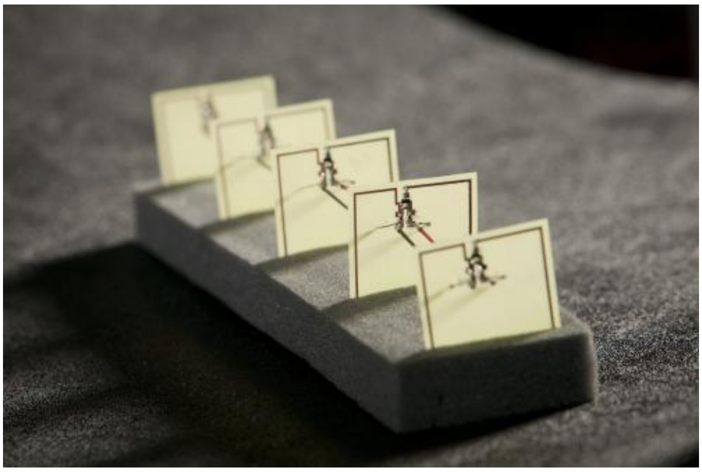


Figure 4-1

Also, there are certain circuits which use RF energy harvesting for other purposes like charging mobile devices [2]. This shows that this technology can, in fact, be applied to a highly useful task of our daily life and therefore, it can be seen as a powerful weapon in a foreseeable future.

As it could be predicted the idea of harvesting energy from electromagnetic waves is not a new one. However, what we aim to accomplish is not a new technology but to improve one. Our objective is to grasp a really low energy and obtain a useful voltage value by using the less amount of external power we could and if it is possible none.

5 Description of requests

As we have mentioned before the aim of this circuit is to recover energy. This is the reason why one of the most crucial requests of this circuit is that it uses the minimum amount of power as possible. Thus, when the circuit is supposed to start up it has to do it with a low voltage input. There are two ways of accomplishing that. The simpler one happens if the circuit is capable of starting up with a low voltage. However, if that is not the case what we would need to do is to use an external battery at the beginning so the circuit can start and when we are able to recover enough energy, in other words, when we have the output voltage needed by the circuit to start use it to do it so and also to recharge the battery. Were we to be in one case or the other the same rule of lower initial power is applied because it results in lower waste of energy and consequently in a more efficient recuperation of energy.

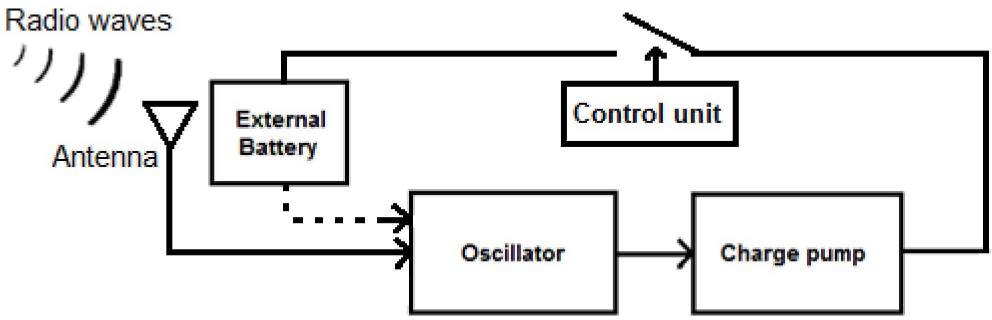


Figure 5-1

In addition, another basic request that can be foreseen is to reach a considerably minimum output voltage. It would not have any sense if we constructed a circuit that could not produce a useful voltage in the output. If the circuit can start up and grab energy but it does not give a profitable output is the same as not working at all. To do the half of the job is equivalent to do nothing. What establish this minimum are the devices which are going to be placed afterwards.

Moreover, if we focus our attention in what are we going to recover we may notice there are many waves we can use. Each of them can be in different frequencies so we need to adapt our system to them. By adapting I mean creating a system which is able to recover energy from one frequency or another depending on what interests us. It may also be said that the wave we choose highly depends on our placement. All of this leads us to the conclusion that we need to establish some variable parameters that can be easily changed when needed. These parameters could be the resistance and capacitances of the circuit which we can conveniently choose.

Last but not least, we also need to bear in mind the cost of the creation, development and construction of the circuit. We cannot pretend to design a circuit whose cost exceeds its benefits from an economic point of view. It would be a loss of time and money and it would not provide anything.

6 Description of different alternatives

The complete circuit can be divided in some sub-circuits which can be studied separately. Among them, a charge pump to increase the voltage and an oscillator to control the last one are required. This is the reason why I am going to divide the explanation of it into these parts.

6.1 Oscillators

Our first aim is to convert the DC power into an AC and this is why at the beginning an oscillator must be placed. However, the challenge of this part is to make the oscillator work with an incredibly low input voltage and without any extra power supply. What we approximately are capable of obtaining from the antenna is 50mV whatever the frequency. With this voltage we need to make our circuit work.

There are many kinds of oscillators nowadays. What we need to do is to study a few and find the one which suits us better. The requirements are simple. First, as I have already mentioned, it must work with low voltage due to the source from where we want to take energy. Because of the same reason, the input power the circuit needs has to be low as well. Last but not least, we should be able to choose in which frequency we want our circuit to work. This is because when we recover energy, it is interesting to be able to choose the wave we want to recover it from and, in order to do that, we need to be able to change the frequency. It goes without saying that the circuit has to be as efficient as possible, in other words, we need to minimize the loss. In order to accomplish that, three different types of oscillators were studied.

It must be said a supply voltage of 1V was supposed for all of them. Although the voltage recovered might be lower it seemed a reasonable value so we could unify the three circuits and see from an objective point of view their performance. In this matter, three different frequencies were also established so that we could study the characteristics of these circuits in them. These are frequencies of approximately 400 kHz, 10 MHz and 100 MHz.

6.1.1 Ring Oscillator

A ring oscillator is a device composed of an odd number of inverters whose output oscillates between two voltage levels, representing true and false. It consists on a series of not gates one after another and the output of the last inverter is fed back into the first.

Because a single inverter computes the 'logical not' of its input, it can be shown that the last output of a chain of an odd number of inverters is the 'logical not' of the first input. This final output is asserted a finite amount of time after the first input is asserted; the feedback of this last output to the input causes oscillation.

A circular chain composed of an even number of inverters cannot be used as a ring oscillator; the last output in this case is the same as the input.

The stages of the ring oscillator are often differential stages that are more immune to external disturbances. This renders available also non inverting stages. The oscillator period is equal to twice the sum of the individual delays of all stages.

A real ring oscillator only requires power to operate; above a certain threshold voltage, oscillations begin spontaneously. To increase the frequency of oscillation, two methods are commonly used. Firstly, the applied voltage may be increased; this increases both the frequency of the oscillation and the current consumed. The maximum permissible voltage applied to the circuits limits the speed of a given oscillator. Secondly, making the ring from a smaller number of inverters results in a higher frequency of oscillation given certain power consumption.

6.1.1.1 Operation

To understand the operation of a ring oscillator one must first understand gate delay. In a physical device no gate can switch instantaneously. In a device made with Mosfets, for example, the gate capacitance must be charged before current can flow between the source and the drain. Thus, the output of every inverter in a ring oscillator changes a finite amount of time after the input has changed. From here, it can be easily seen that adding more inverters to the chain increases the total gate delay, reducing the frequency of oscillation.

The ring oscillator is a member of the class of time delay oscillators. A time-delay oscillator consists of an inverting amplifier with a delay element between the amplifier output and its input. The amplifier must have a gain of greater than 1.0 at the intended oscillation frequency. Consider the initial case where the amplifier input and output voltages are momentarily balanced at a stable point. A small amount of noise can cause the amplifier output to rise slightly. After passing through the time-delay element, this small output voltage change will be presented to the amplifier input. The amplifier has a negative gain of greater than 1, so the output will change in the direction opposite to this input voltage. It will change by an amount larger than the input value, for a gain of greater than 1. This amplified, reversed signal propagates from the output through the time-delay and back to the input, where it is amplified and inverted again. The result of this sequential loop is a square-wave signal at the amplifier output with the period of each half of the square wave equal to the time delay. The square wave will grow until the amplifier output voltage reaches its limits, where it will stabilised.

The ring oscillator is a distributed version of the delay oscillator. The ring oscillator uses an odd number of inverters to give the effect of a single inverting amplifier with a gain of greater than one. Rather than having a single delay element, each inverter contributes to the delay of the signal around the ring of inverters, hence the name ring oscillator. Adding pairs of inverters to the ring increases the total delay and thereby decreases the oscillator frequency. Changing the supply voltage changes the delay through each inverter, with higher voltages typically decreasing the delay and increasing the oscillator frequency. However, in this case this is not an option because we are not in control of the supply voltage as it comes from what we recover. Indeed, we need to be able to change frequency regardless of the input voltage. This is why it can be also considered as an option changing the capacitors that can be placed between one logical door and the next one so they introduce more or less delay time.

If 'T' represents the time-delay for a single Inverter and 'N' represents the number of Inverters in the Inverter chain, then the frequency of oscillation is given by $= \frac{1}{2 \cdot N \cdot T}$. [3]

Once we understand how does the oscillator ring work is time to view the results we obtained with this kind of circuit.

6.1.1.2 Simulation

For the simulation a 5 stage ring oscillator as the following was used.

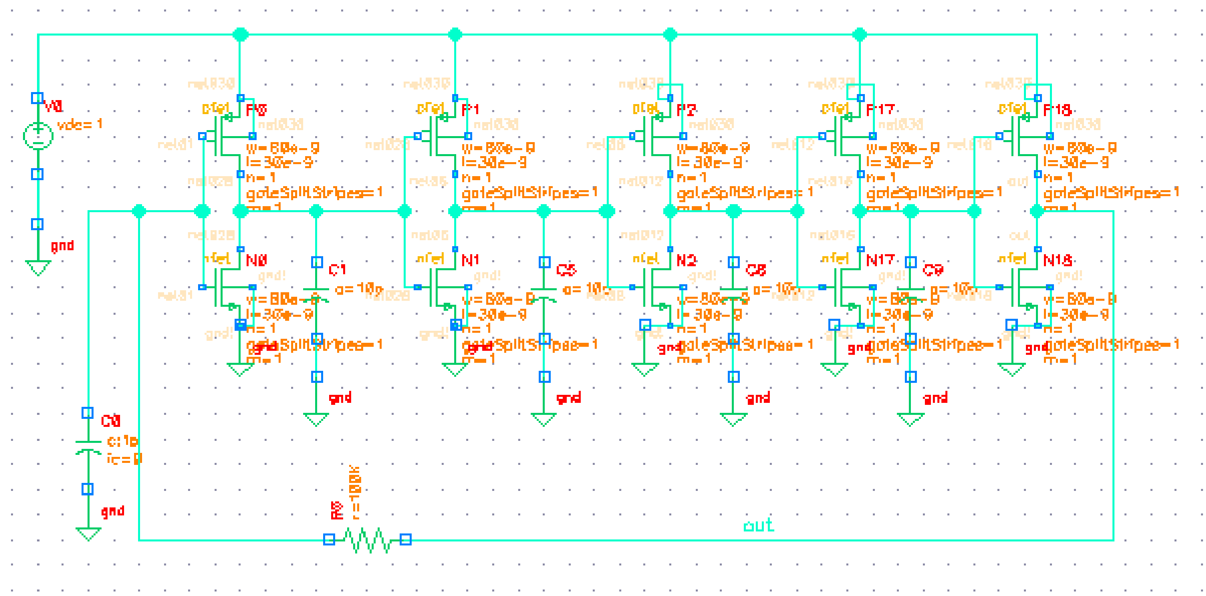


Figure 6-1

We selected five stages to reach enough delay time. It can be possible to increase the number of stages, but the power consumption will increase.

Depending on the frequency:

a. f= 400 KHz

C=10 pF

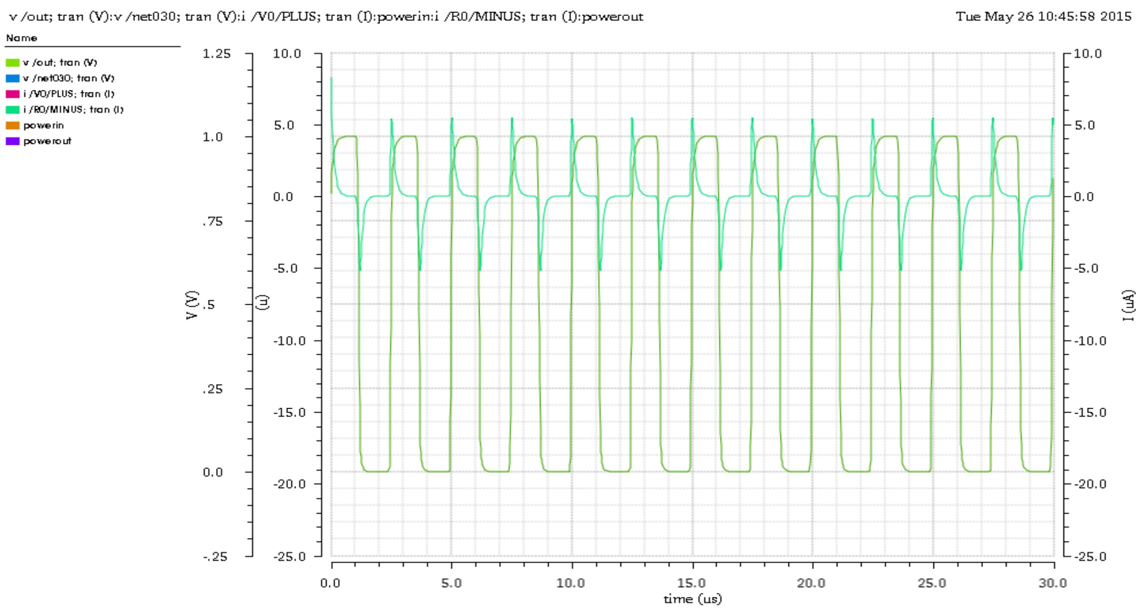


Figure 6-2 Output voltage and intensity

We can observe the oscillating wave in clear green which goes up to 1V as the input voltage.

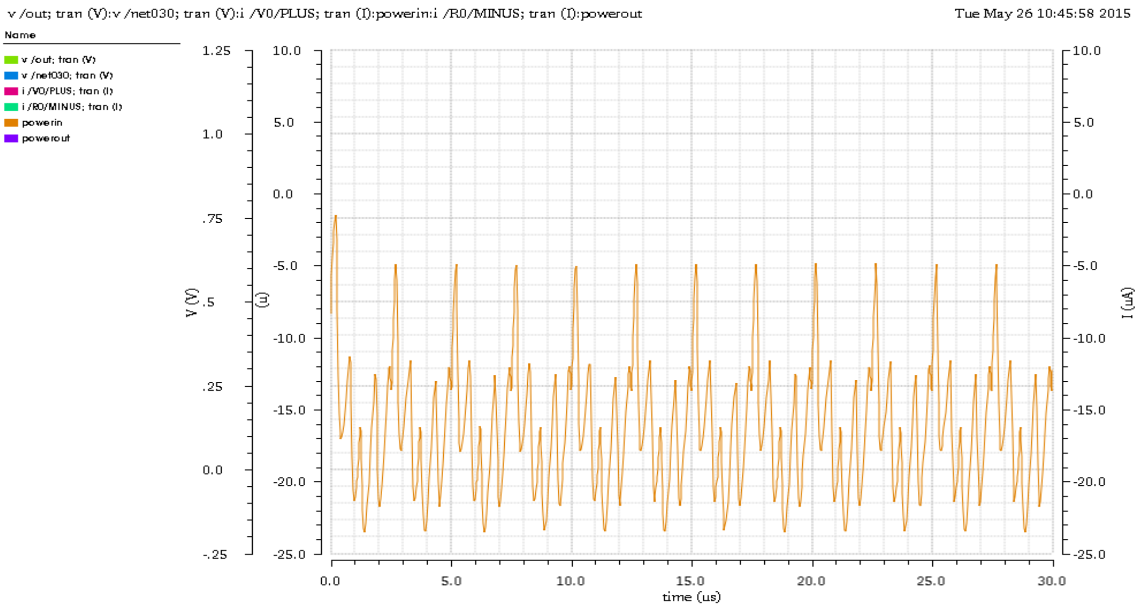


Figure 6-3 Input power

The input power gives an exit quite changeable.

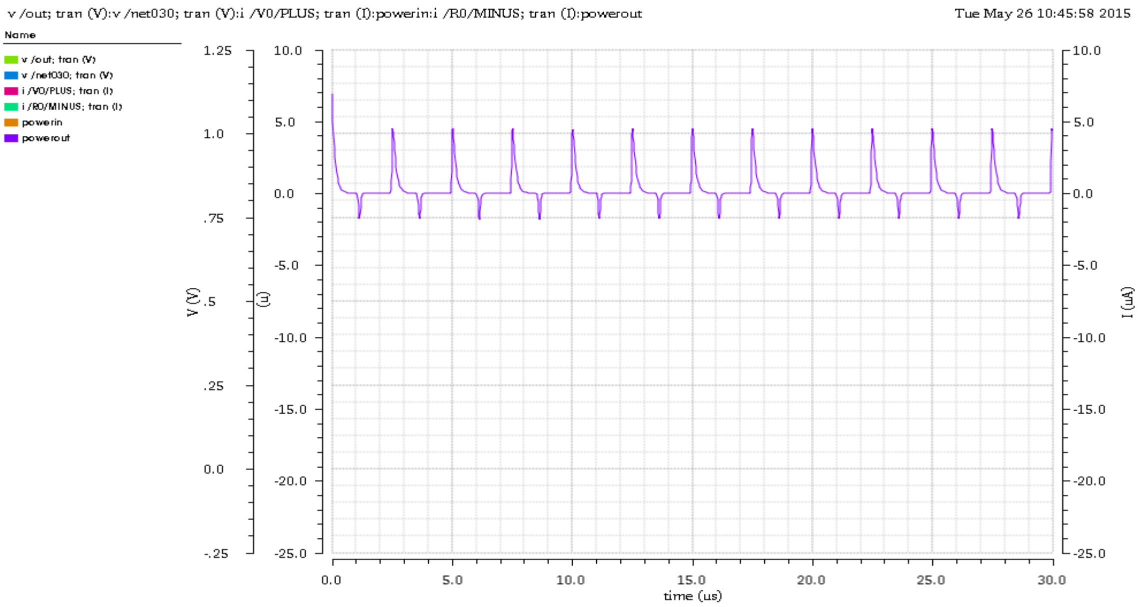


Figure 6-4 Output power

b. f= 12MHz

C=0,05pF

The oscillation for this frequency gives a little bit less voltage than the previous case.

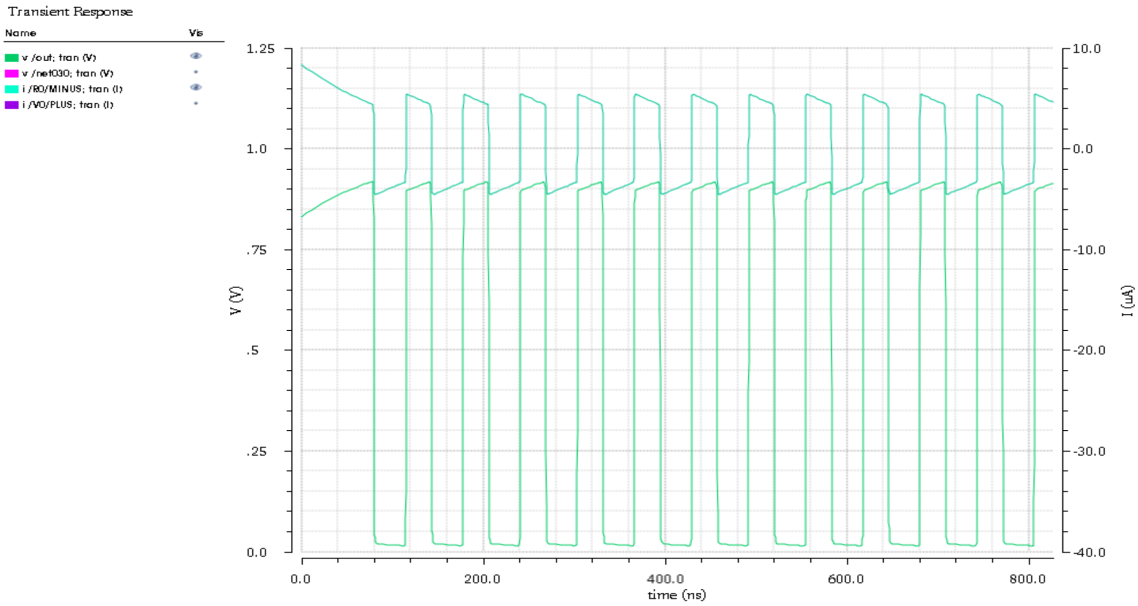


Figure 6-5 Output

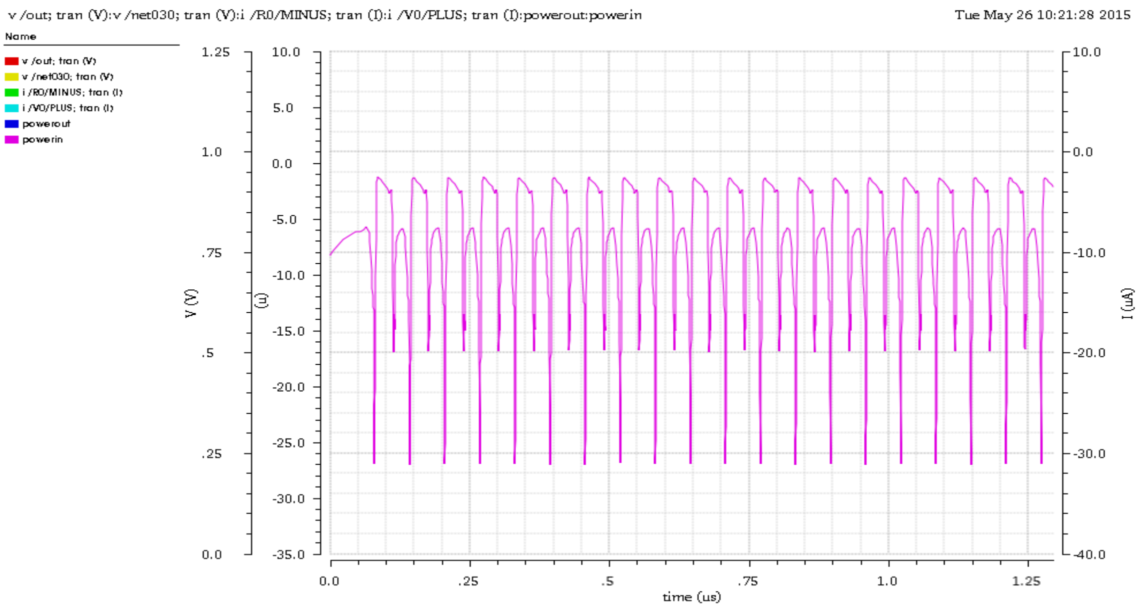


Figure 6-6 Input power

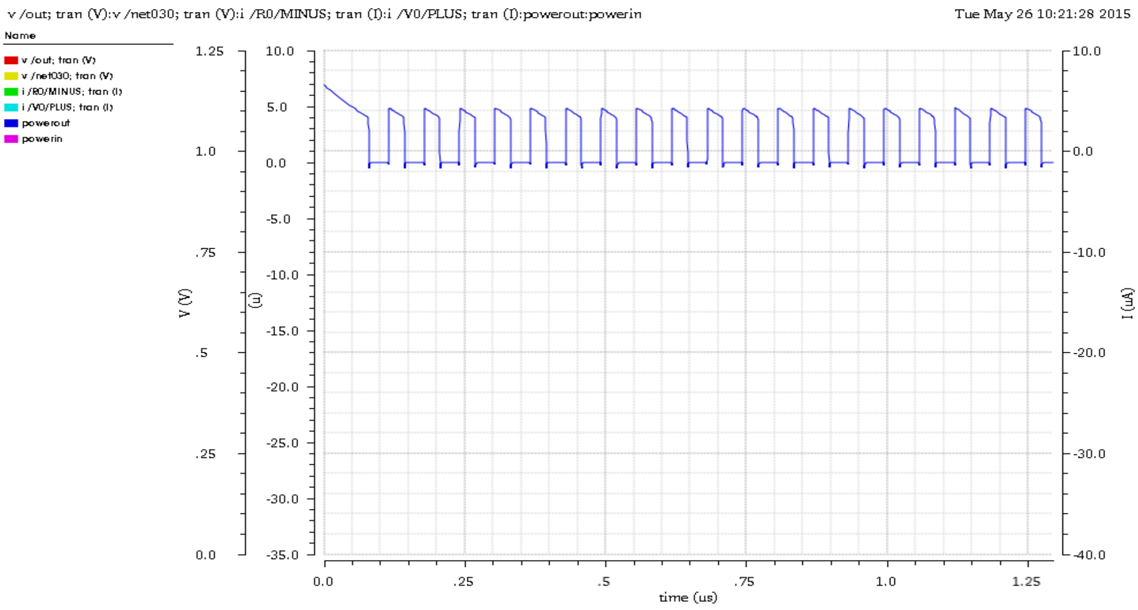


Figure 6-7 Output power

The input and output power are more similar to an organised wave.

c. f~110 MHz

C=0,004 pF

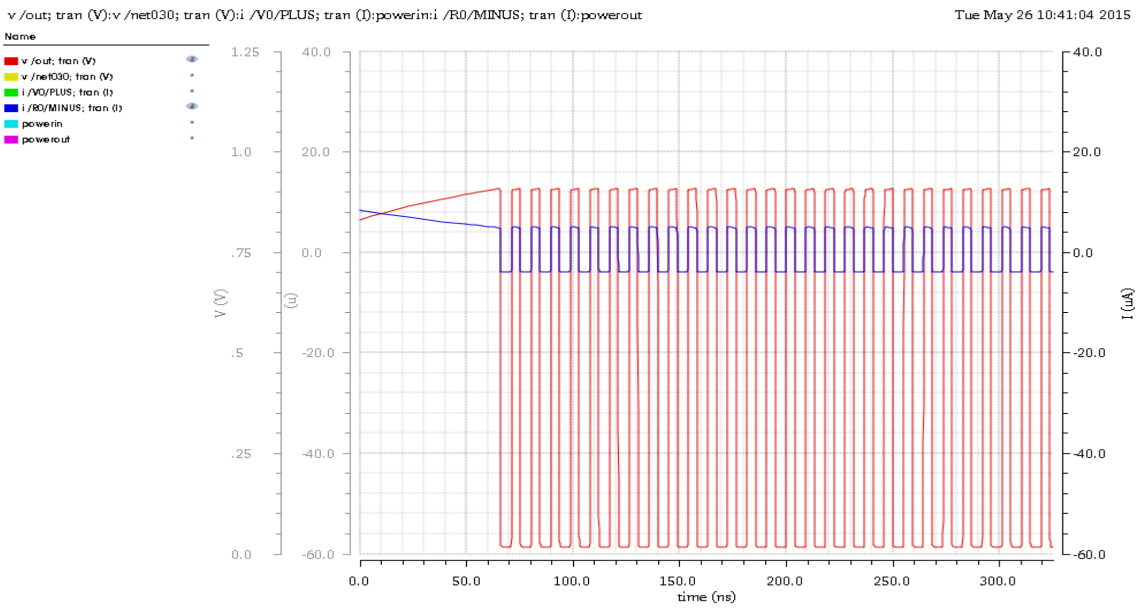


Figure 6-8 Output

The output voltage does not reach the value of the input one.

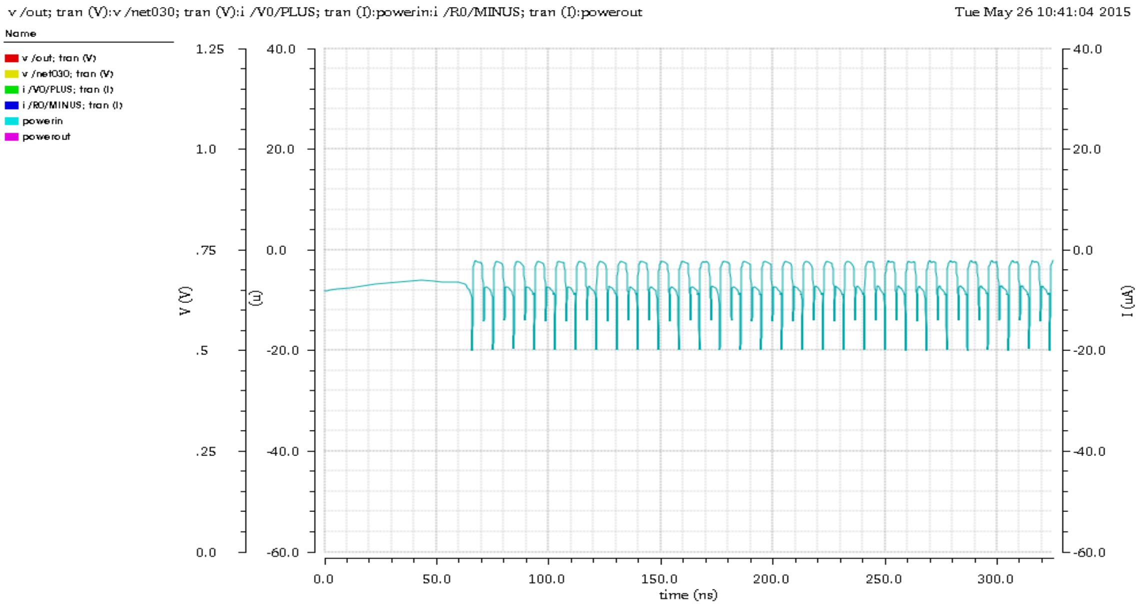


Figure 6-9 Input power

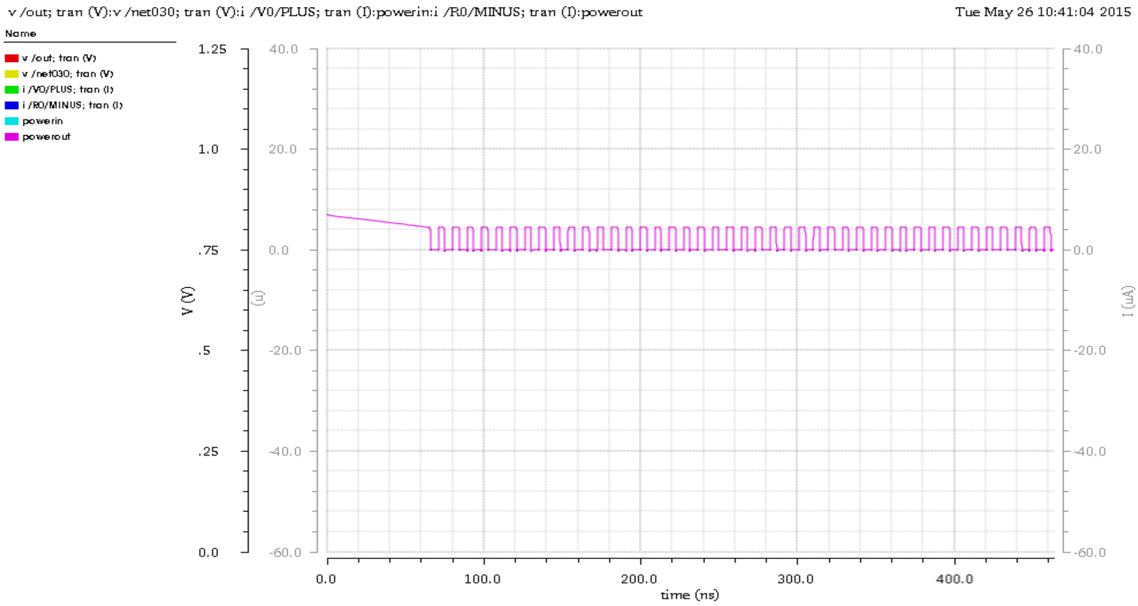


Figure 6-10 Output power

6.1.2 Astable

What made us choose the astable multivibrator is the fact that unlike the monostable or the bistable it does not require an external trigger pulse, in fact, it has an automatic built in triggering which switches between two unstable states.

An astable multivibrator consists of two amplifying stages connected in a positive feedback loop by two capacitive-resistive coupling networks. The amplifying elements may be junction or field-effect transistors, vacuum tubes, operational amplifiers, or other types of amplifier. The example diagram shows bipolar junction transistors.

The astable multivibrator belongs to the cross-coupled transistors and it has no stable output state, that is, it changes from one state to the other all the time. The astable circuit consists of two switching transistors, a cross-coupled feedback network, and two time delay capacitors which allow oscillation between the two states with no external trigger signal to produce the change in state.

In electronic circuits, astable multivibrators are also known as free-running multivibrators as they do not require any additional inputs or external assistance to oscillate.

The basic transistor circuit for an astable multivibrator produces a square wave output from a pair of grounded emitter cross-coupled transistors. Both transistors either NPN or PNP, in the multivibrator are biased for linear operation and are operated as common emitter amplifiers with 100% positive feedback.

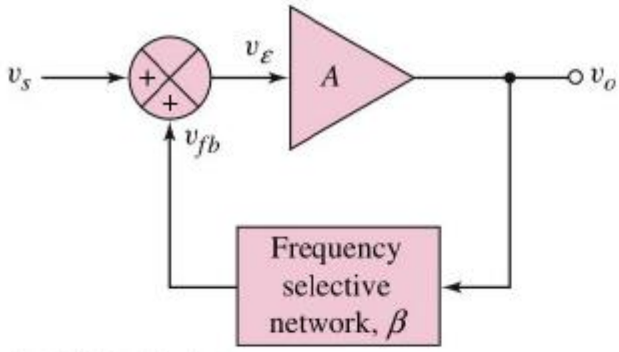


Figure 6-11

This configuration satisfies the condition for oscillation when: (βA = 1+j0). This means that the loop gain is unitary and that the feedback should be positive. This results in one stage conducting “fully-ON” (saturation) while the other is switched “fully-OFF” (cut-off) giving a very high level of mutual amplification between the two transistors. Conduction is transferred from one stage to the other by the discharging action of a capacitor through a resistor.

The amplitude of the output waveform is approximately the same as the supply voltage, Vcc with the time period of each switching state determined by the time constant of the RC networks connected across the base terminals of the transistors. As the transistors are switching both “ON” and “OFF”, the output at either collector will be a square wave with slightly rounded corners because of the current which charges the capacitors.

If the two time constants produced by the two products C2xR2 and C1XR3 in the base circuits are the same, the mark-to-space ratio (t1/t2) will be equal to one-to-one making the output waveform symmetrical in shape. By varying the capacitors or the resistors R2 and R3 the mark-to-space ratio and therefore the frequency can be altered. [4]

6.1.2.1 Operation

Suppose that at switch on, TR1 is conducting heavily and TR2 is turned off. The collector of TR1 will be almost at zero volts as will the left hand plate of C1. Because TR2 is turned off at this time, its collector will be at supply voltage and its base will be at almost zero potential, the same as TR1 collector, because C1 is still un-charged and its two plates are at the same potential.

C1 now begins to charge via R2 and its right hand plate becomes increasingly positive until it reaches a voltage of about +0.6V. As this plate of the capacitor is also connected to the base of TR2, this transistor will begin to conduct heavily. The rapidly increasing collector current through TR2 now causes a voltage drop across R4, and TR2 collector voltage falls, causing the right hand plate of C2 to fall rapidly in potential.

It is the nature of a capacitor that when the voltage on one plate changes rapidly, the other plate also undergoes a similar rapid change, therefore as the right hand plate of C2 falls rapidly from supply voltage to almost zero, the left hand plate must fall in voltage by a similar amount. [5]

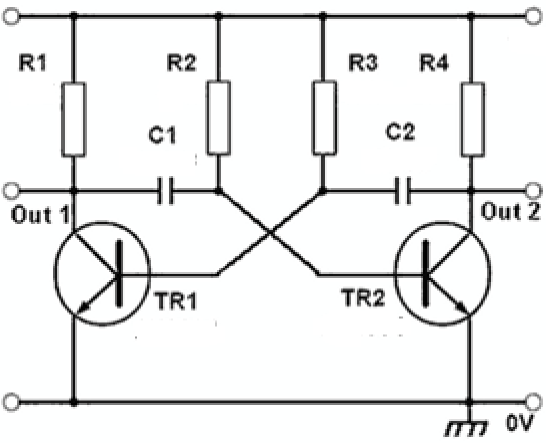


Figure 6-12

With TR1 conducting, its base would have been about 0.6V, so as TR2 conducts TR1 base falls to 0.6 −9V = −8.4V, a negative voltage almost equal and opposite to that of the +9V supply voltage.

This rapidly turns off TR1 causing a rapid rise in its collector voltage. Because a sudden voltage change on one plate of a capacitor causes the other plate to change by a similar amount, this sudden rise at TR1 collector is transmitted via C1 to TR2 base causing TR2 to rapidly turn on as TR1 turns off. A change of state has occurred at both outputs.

This new state does not last however. C2 now begins to charge via R3, and once the voltage on the left hand plate (TR1 base) reaches about +0.6V another rapid change of state takes place.

The circuit keeps on changing state in this manner producing a square wave at each collector. The frequency of oscillation can be calculated, as the time for the relevant capacitor to charge sufficiently for a change of state to take place, will be approximately 0.7CR and, as two changes of state occur in each cycle the periodic time T will be:

$$T = 1{,}4 \cdot (C1 \cdot R2 + C2 \cdot R3) \text{ [a]}$$

If C1 = C2 and R2 = R3 the mark to space ratio will be 1:1 and in this case the frequency of oscillation will be:

$$f_0 = \frac{1}{1{,}4 \cdot C \cdot R} \text{ [b]}$$

When starting to simulate this circuit a first problem appeared. The devices used are ideal so when starting to simulate what happened is that the two transistors began to conduct at the same time and there was no difference between them. This resulted into nothing because the circuit would not start oscillating. In order to solve this problem another capacitor was placed the way it is shown in the figure 6-13. This capacitor is initially charged and therefore creates a difference between the two transistors and so forth the circuit begins to oscillate.

With the aim of reaching the three different frequencies accorded the main capacitances were changed. At the very beginning, this circuit would not start oscillating. After some investigations a problem with the transistors seemed to be the cause and they had to be enlarged. This way, they were able to let more current pass by them and consequently the circuit started. The number of emitters was raised from 1 to 10 and because of that the base area was enlarged too. At this point the circuit began to work so now the correct frequency had to be searched and the input power minimized.

By changing some of the parameters two of the three frequencies were accomplished. When trying to reach the highest one, the circuit stopped to oscillate. This circuit was only able to reach a frequency of 50MHz.

Here there is a table showing which were the values established to each component to achieve the different frequencies. It must be said though that some values were slightly modified when putting together the oscillator and charge pump because by doing it the frequency changed a little bit.

Frequency [kHz]	R1 [kΩ]	R2 [kΩ]	R3 [kΩ]	R4 [kΩ]	C [pF]	Cp [fF]	Transistor number of fingers
400	4	50	50	4,01	150	1	1
$10 \cdot 10^3$	1,1	120	120	1	4	1	5
$100 \cdot 10^3$	1	15	15	1,01	0,6	10	10

Table 6-1

6.1.2.2 Simulation

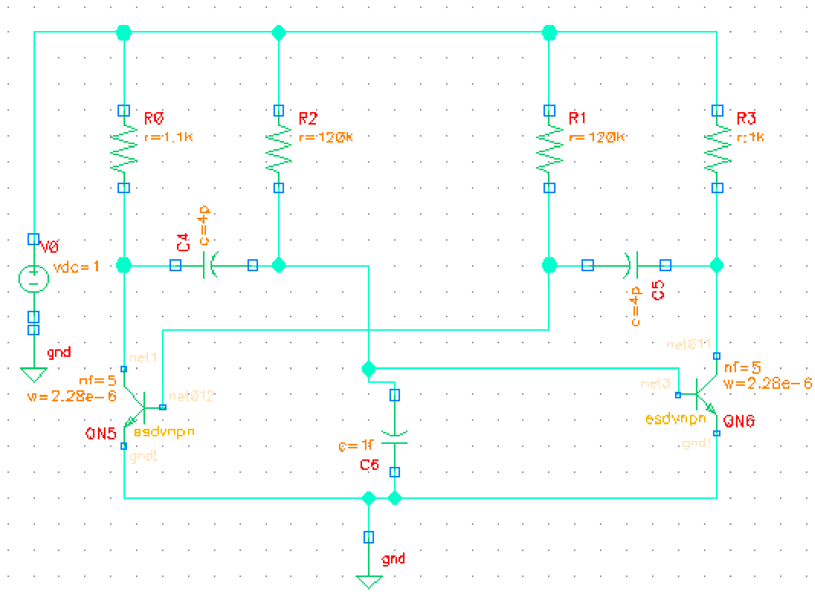


Figure 6-13

The results reached are the following.

1) f=400 kHz

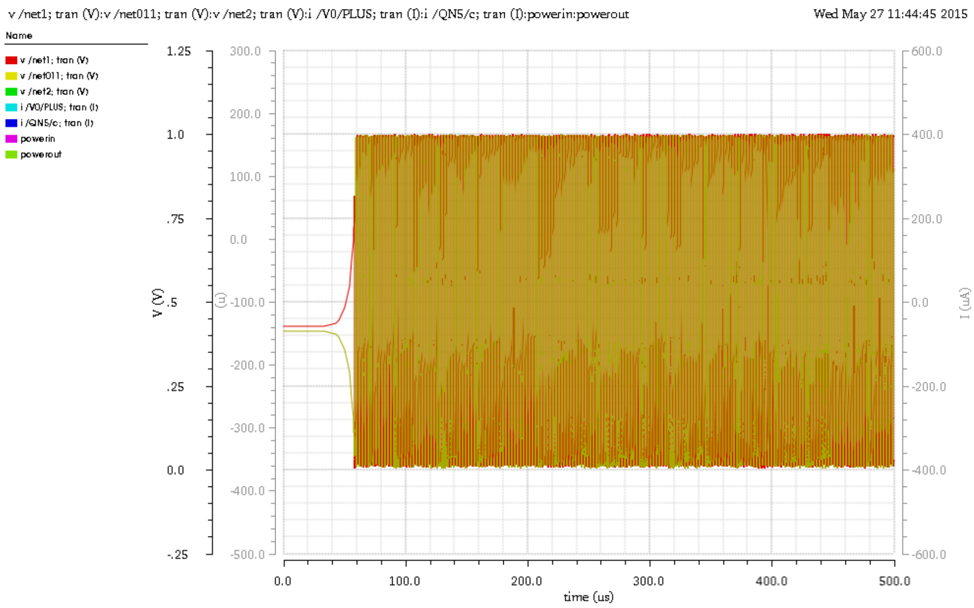


Figure 6-14 Output

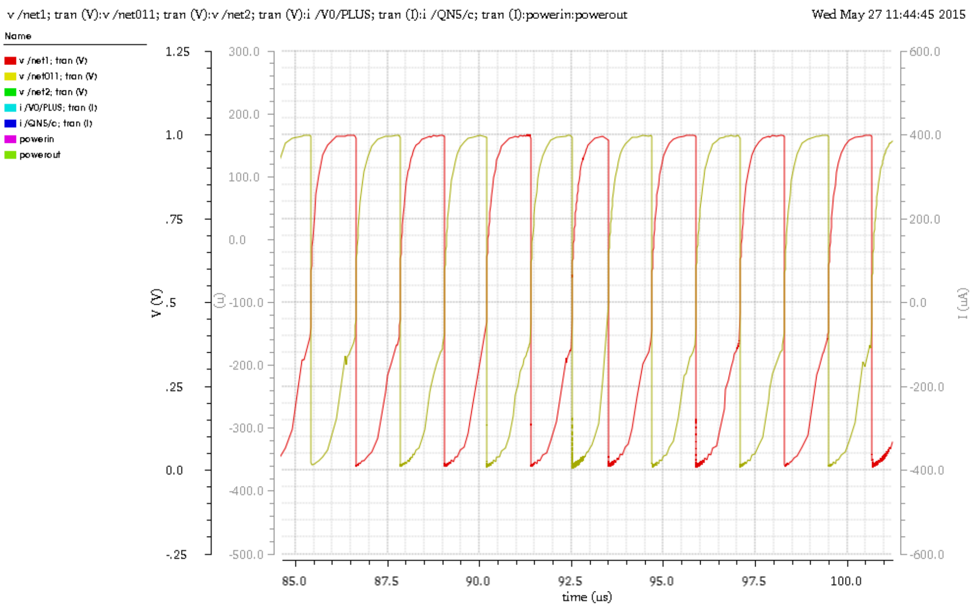


Figure 6-15 Output

Here we see the two oscillating waves this circuit gives in its two outputs. They are opposed in phase and reach the initial value of 1V.

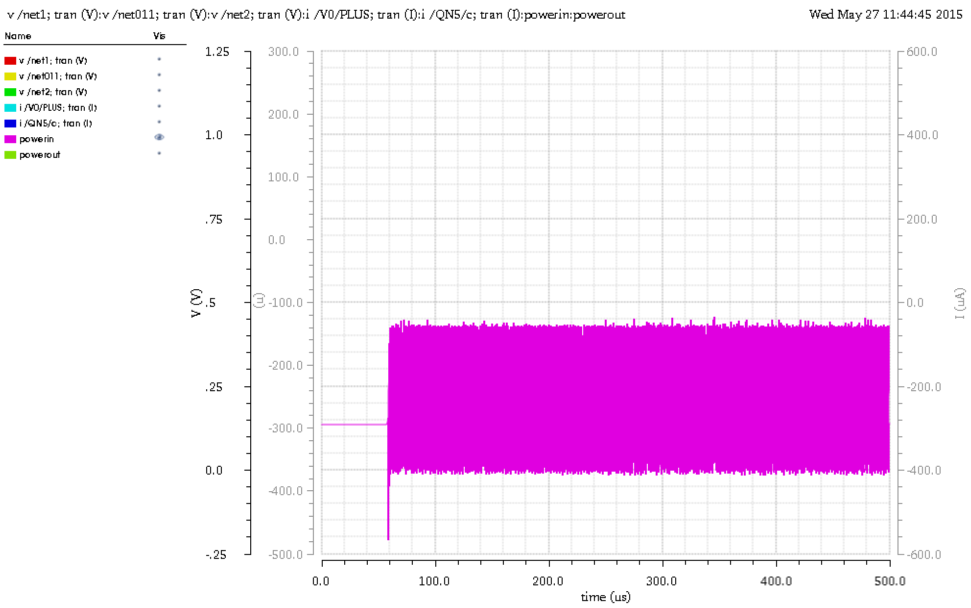


Figure 6-16 Input power

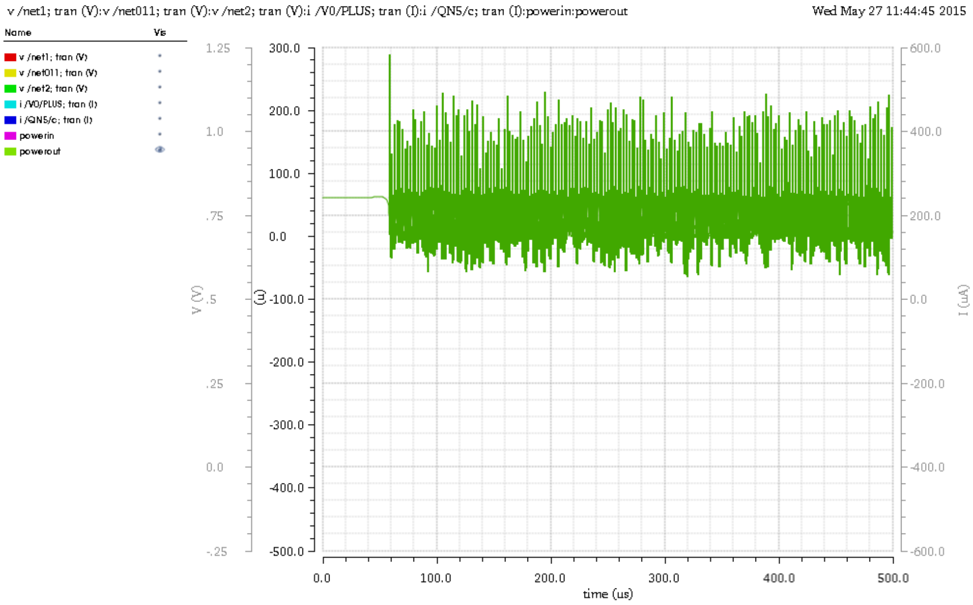


Figure 6-17 Output power

2) f=10MHz

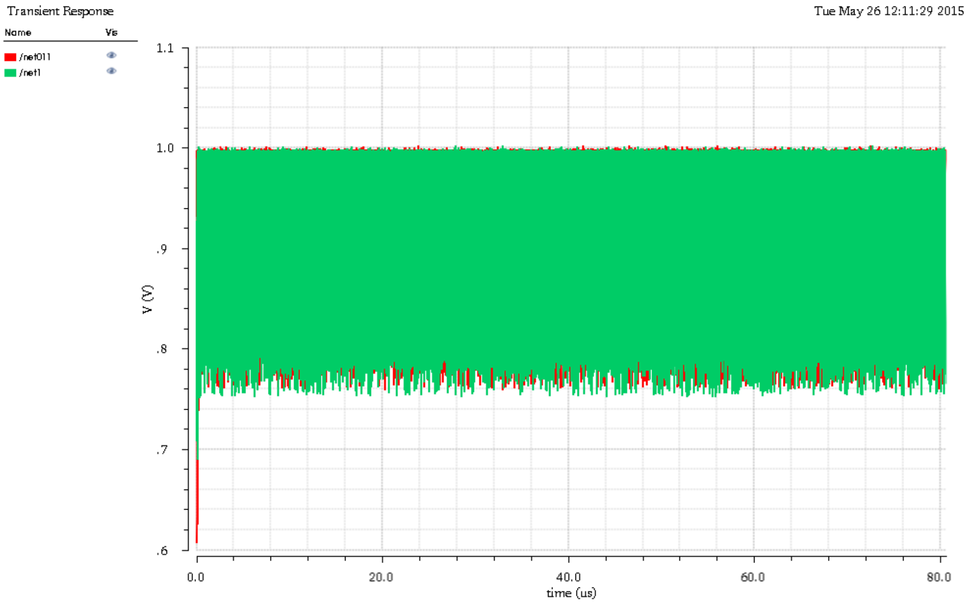


Figure 6-18 Output

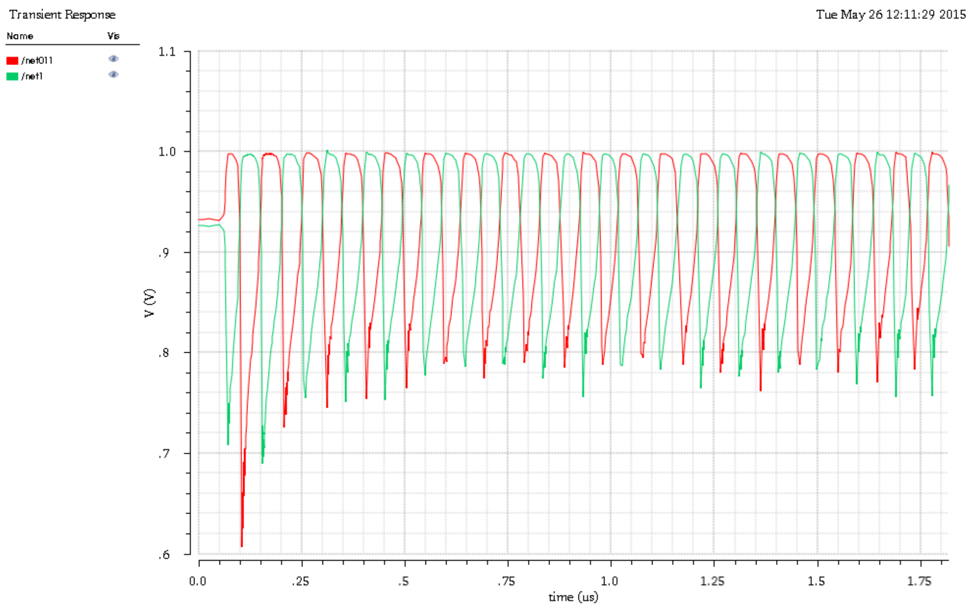


Figure 6-19 Output

We can observe that the oscillations of the two outputs do not finish the oscillation completely. This is because the capacitor does not charge completely.

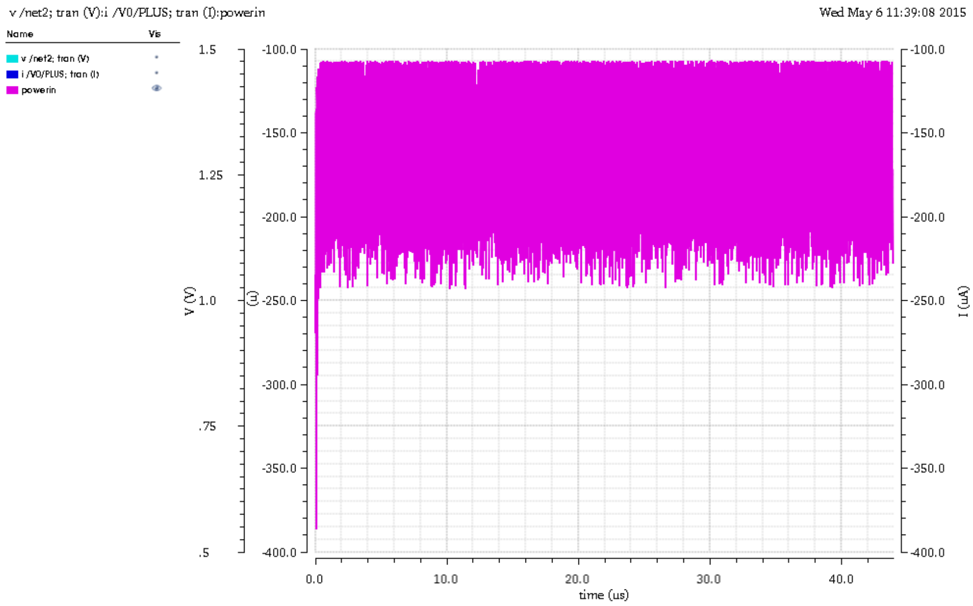


Figure 6-20 Input power

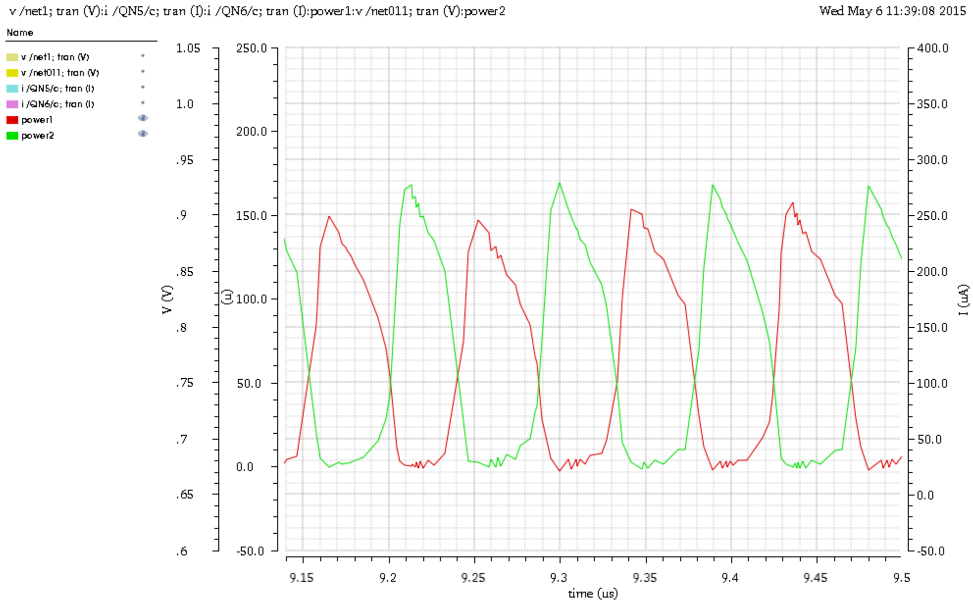


Figure 6-21 Output power

6.1.3 Comparison

In the previous points we have used either the ring oscillator or the astable in order to generate an oscillating wave in the different frequencies established at the beginning. It is time then to make a comparison between the different values that have been obtained thus we can conclude which one is the most appropriate.

f = 400 kHz

Oscillator	Output voltage [V]	Input power [W]	Output power [W]	Consumed power [W]
Ring	1	$23 \cdot 10^{-6}$	$4 \cdot 10^{-6}$	$19 \cdot 10^{-6}$
Astable	1	$370 \cdot 10^{-6}$	$70 \cdot 10^{-6}$	$300 \cdot 10^{-6}$

Table 6-2

f = 10 MHz

Oscillator	Output voltage [V]	Input power [W]	Output power [W]	Consumed power [W]
Ring	0,92	$26 \cdot 10^{-6}$	$5 \cdot 10^{-6}$	$21 \cdot 10^{-6}$
Astable	0,98	$230 \cdot 10^{-6}$	$150 \cdot 10^{-6}$	$80 \cdot 10^{-6}$

Table 6-3

f = 100 MHz

Oscillator	Output voltage [V]	Input power [W]	Output power [W]	Consumed power [W]
Ring	0,92	$20 \cdot 10^{-6}$	$6 \cdot 10^{-6}$	$14 \cdot 10^{-6}$
Astable[1]	0,94	$0{,}98 \cdot 10^{-3}$	$340 \cdot 10^{-6}$	$640 \cdot 10^{-6}$

Table 6-4

It must be mentioned that the values taken for power and voltage are the maximum ones and that if any power value happens to be negative is due to the way the intensity is taken therefore, it is considered as positive.

Once the results come out a few things can be pointed out.

First, the biggest drawback of the astable is that it has been a difficult task to establish the desired frequency. It was very easily made unstable and consequently it didn't start oscillating. As a result, the last frequency could not be reached and the maximum achieved was 50 MHz. This is an important shortage as it is basic in order to be able to recover energy.

Furthermore, the input power needed by the astable is higher than the one needed by the ring and it consumes more power as well. This means that the last circuit will be capable of oscillating with a lower amount of energy recovered even if the output power accomplished is lower.

These two characteristics are highly desirable for our circuit. Therefore, I believe the best option between a ring and an astable oscillator is the ring one not only because of its results but also because of its simplicity.

6.2 Charge pump

Once an oscillating wave is accomplished the next step is to enlarge its potential so it can be of some use. Several methods exist to achieve DC-DC voltage conversion. Each of these methods has its specific benefits and disadvantages, depending on a number of operating conditions and specifications. Examples of such specifications are the voltage conversion ratio range, the maximal output power, power conversion

[1] *As the astable does not arrive up to 100 MHz these values stand for a frequency of 50 MHz.*

efficiency, number of components, power density, galvanic separation of in and output, etc. When designing fully-integrated DC-DC converters these specifications generally remain relevant, nevertheless some of them will gain weight, as more restrictions emerge. A perfectly suitable circuit to do that is a charge pump circuit. This is because this kind of circuit is often the best choice for powering an application that requires both low power and low cost.

A charge pump is a kind of DC to DC converter that uses capacitors as energy storage elements to create either a higher or lower voltage power source. Charge pump circuits are capable of high efficiencies, sometimes as high as 90–95% while being electrically simple circuits. Charge pumps can double voltages, triple voltages, halve voltages, invert voltages, fractionally multiply or scale voltages (such as x3/2, x4/3, x2/3, etc.) and generate arbitrary voltages by quickly alternating between modes, depending on the controller and circuit topology.

6.2.1 Dickson charge pump

6.2.1.1 Operation

The Dickson charge pump circuit consists of two pumping clocks, ϕ and ϕ' which are anti-phase and have a voltage amplitude of V_{ϕ}. The diodes operate as self-timed switches characterized by a forward bias voltage, V_d. Stray capacitance, C_s, is included at each node for completeness. [6]

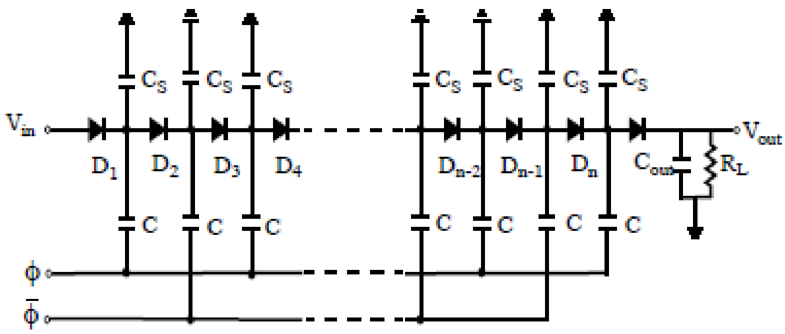


Figure 6-22

The multiplier operates by pumping charge along diode chain as the capacitors are successively charged and discharged during each clock cycle. When clock phase ϕ goes low, diode D_1 conducts until the voltage at node 1 becomes V_{in}-V_d. When ϕ is switched to Vϕ, the voltage at node 1 bow becomes V_{in} + (Vϕ -V_d). This causes diode D_2 to conduct until the voltage at node 2 becomes equal to V_{in} + (Vϕ -V_d) –V_d . When ϕ goes low again, the voltage at node 2 becomes V_{in} + 2(Vϕ -V_d). After N stages, it is easy to see that the output voltage is:

$$V_{out} = V_{in} + N \cdot (V_\phi - V_d) - V_d \quad [c]$$

The stray capacitance, C_s, can be taken into account by noticing that it reduces the transferred clock voltage Vϕ, by a factor: $\frac{C}{C+C_s}$. Thus, the actual output voltage becomes:

$$V_{out} = V_{in} + N \cdot \left(\left(\frac{C}{C+C_s}\right) \cdot V_\phi - V_d\right) - V_d \quad [d]$$

If we consider a load at the output, the output voltage is reduced by an amount $\frac{N \cdot I_{out}}{(C+C_s) \cdot f_{osc}}$ where f_{osc} is the operating frequency of the charge pump. The output voltage now becomes:

$$V_{out} = V_{in} + N \cdot \left(\left(\frac{C}{C+C_s}\right) \cdot V_\phi - V_d - \frac{I_{out}}{(C+C_s) \cdot f_{osc}}\right) - V_d \quad [e]$$

From this equation it becomes clear that voltage multiplication occurs only if:

$$\left(\frac{C}{C+C_s}\right) \cdot V_\phi - V_d - \frac{I_{out}}{(C+C_s) \cdot f_{osc}} > 0 \quad [f]$$

It should be noted that there will be a small ripple voltage V_R at the output due to the load resistance which can be substantially reduced by increasing the frequency of the clocks or using a large output capacitance.

A practical circuit implementation of the Dickson charge pump is CMOS technology which is implemented using diode-connected NMOS transistors. Here the diode forward voltage V_d is replaced by the MOS threshold voltage V_{tn} and the output voltage is given by:

$$V_{out} = V_{in} + N \cdot \left(\left(\frac{C}{C+C_s}\right) \cdot V_\phi - V_{tn} - \frac{I_{out}}{(C+C_s) \cdot f_{osc}}\right) - V_{tn} \quad [g]$$

We can define the voltage pumping gain G_V:

$$G_v = V_N - V_{N-1} \quad [h]$$

Unfortunately, as the supply voltage decreases, Vϕ decreases and the pumping gain is also reduced. The basic idea is to use MOS switches with precise on/off characteristics to direct charge flow during pumping rather than using diodes or diode connected transistors.

6.2.1.2 Simulation

A 4 stage Dickson charge pump was used.

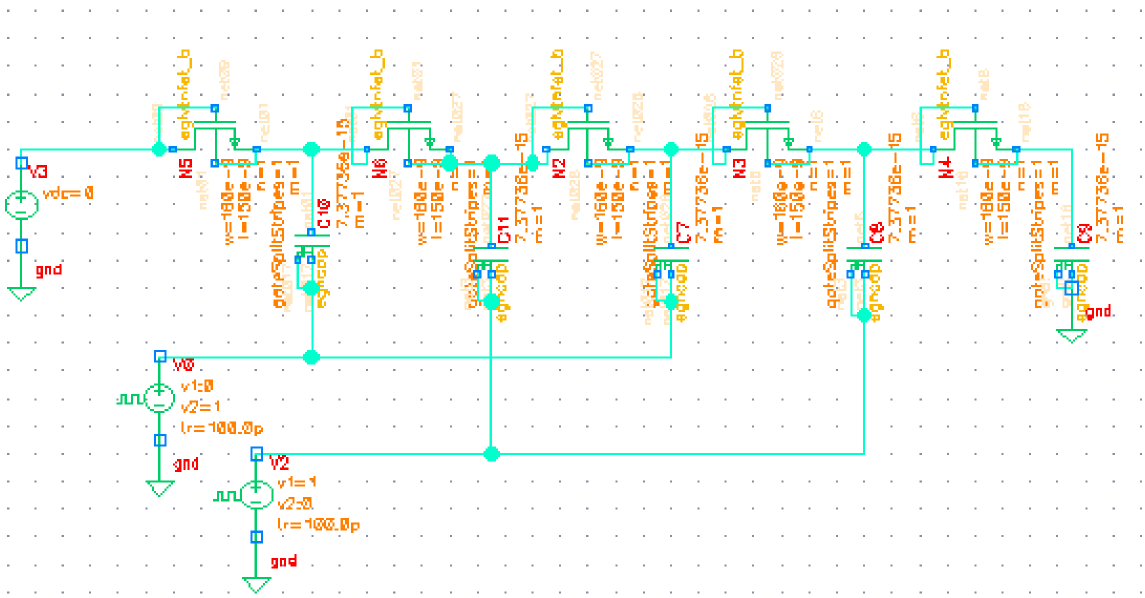


Figure 6-23

a. f=400 kHz

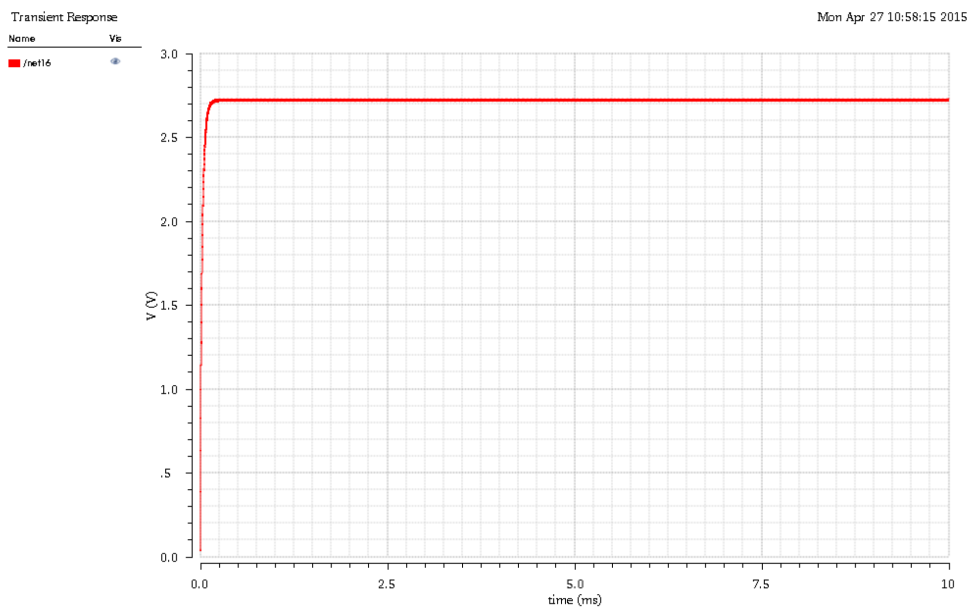


Figure 6-24

b. f=10MHz

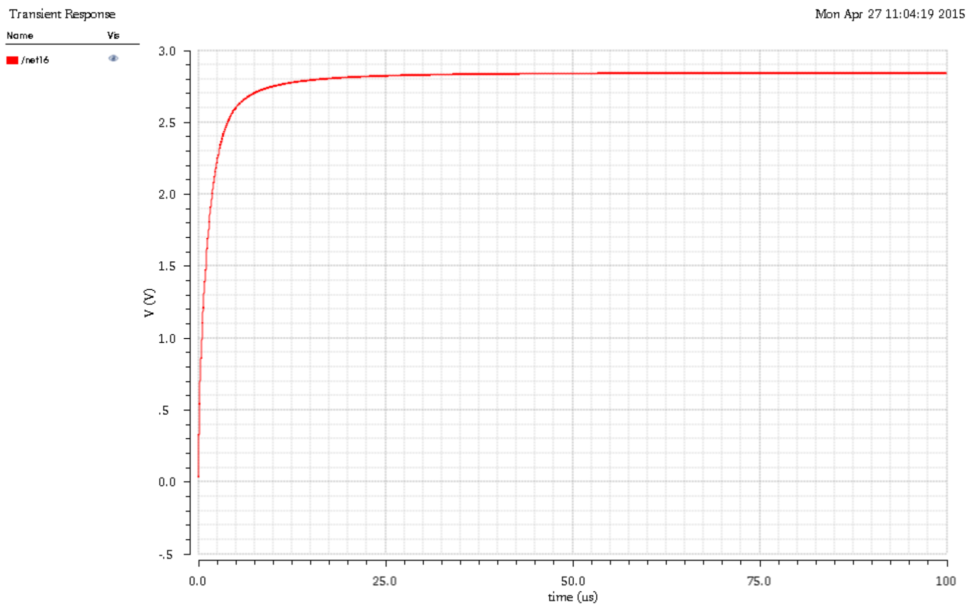


Figure 6-25

c. f=100MHz

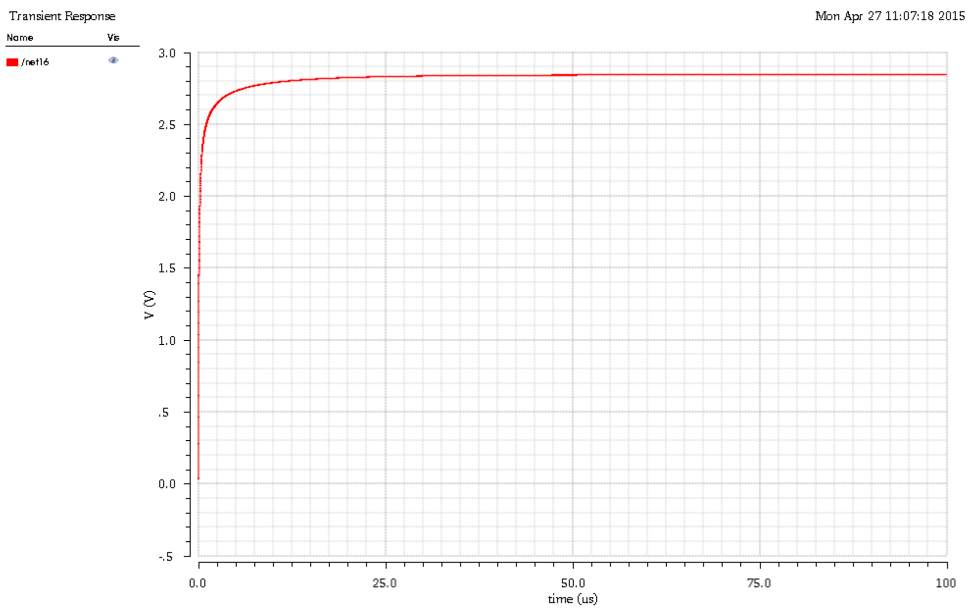


Figure 6-26

We can observe than in the three previous figures the voltage is actually higher than the double of the input voltage which is a good result.

Since we have established an initial input voltage of 1V it is also seems interesting to indicate which is the minimum voltage that enables the charge pump to work. In other words, until what value of voltage can this circuit give a higher output.

Minimum voltage=35mV

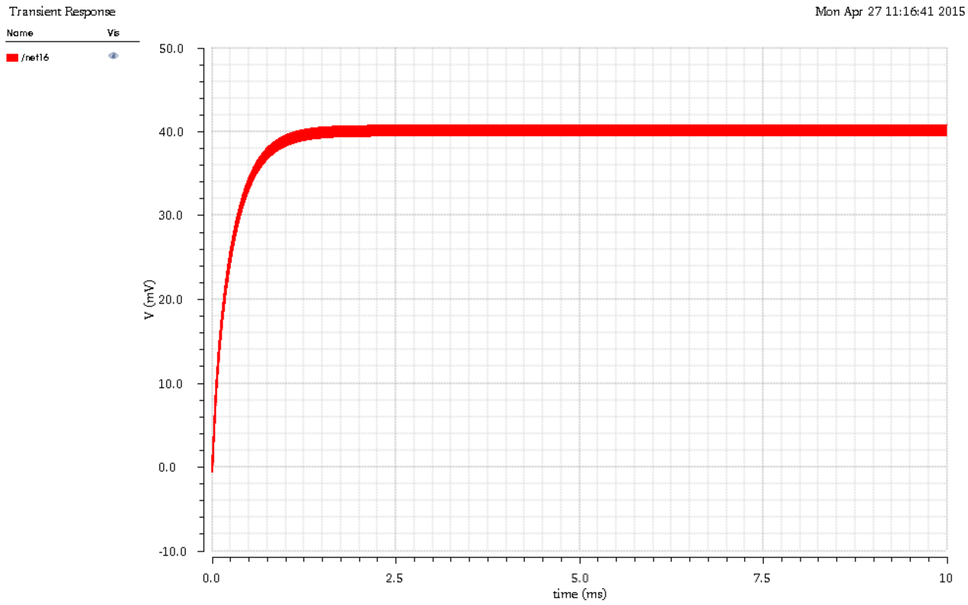


Figure 6-27

6.2.2 Cross coupled charge pump

6.2.2.1 *Operation*

The famous cross-coupled topology was first proposed by Y.Nakagome et al. The clock system generates two non-overlapping clocks and feeds them to the bottom plate of the capacitors. At steady state, during phase one, the clock signal boosts C_1 up. If we assume C_1 has already been charged to V_{DD} during the previous phase and the clock signal swing is V_{DD}, the voltage level at the top plate of goes to $2V_{DD}$ and meanwhile PMOS M3 turns on, and C_1 discharges to the load. At the same time, the bottom plate of C_2 is grounded and NMOS M2 turns on and PMOS M4 turns off since the gate of M2 which is also the gate of M4 goes to $2V_{DD}$. This makes C_2 charge up to V_{DD} and be ready to be discharged. During phase two, the flying capacitors C_1 and C_2 swap their roles: the gate of NMOS M1 (which is also the gate of PMOS M3) going high turns M1 on and M3 off, so C_1 gets charged; the gate of NMOS M2 and PMOS M4 reduces to approximately , turning M2 off and M4 on, and gets discharged to the load. We choose NMOS devices for the charging path because they provide automatic junction bias. We use PMOS devices for the output switch to avoid the threshold voltage drop from the pumping capacitors to the output capacitor because there is no higher voltage beyond $2V_{DD}$. Interestingly, as we can see in this topology, all the four switches are driven internally. [7]

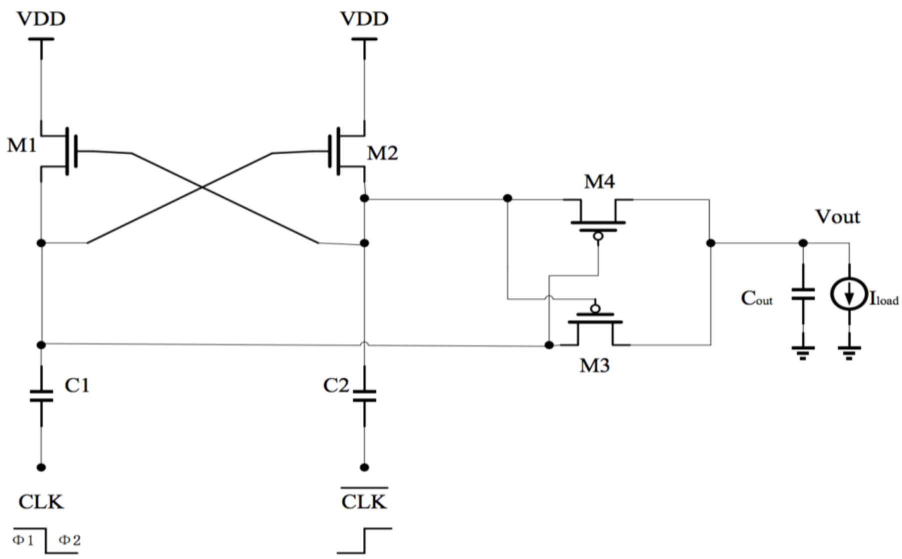


Figure 6-28

6.2.2.2 Simulation

The cross-coupled charge pump used is the following.

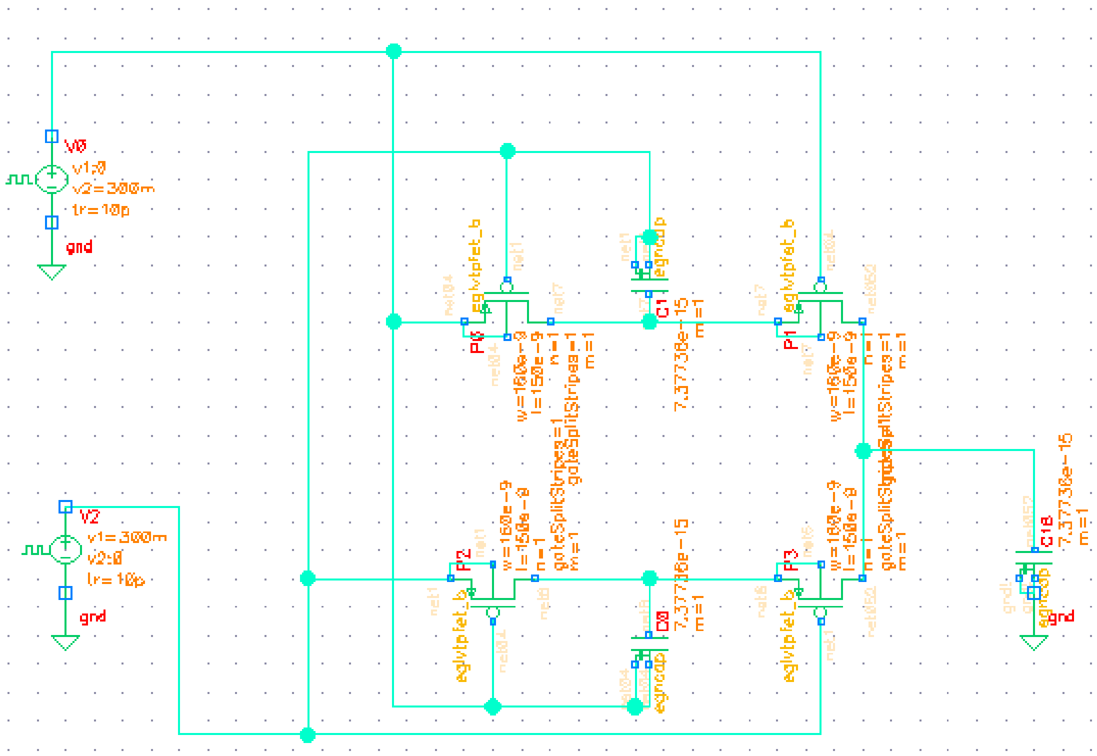


Figure 6-29

a. f=400 kHz

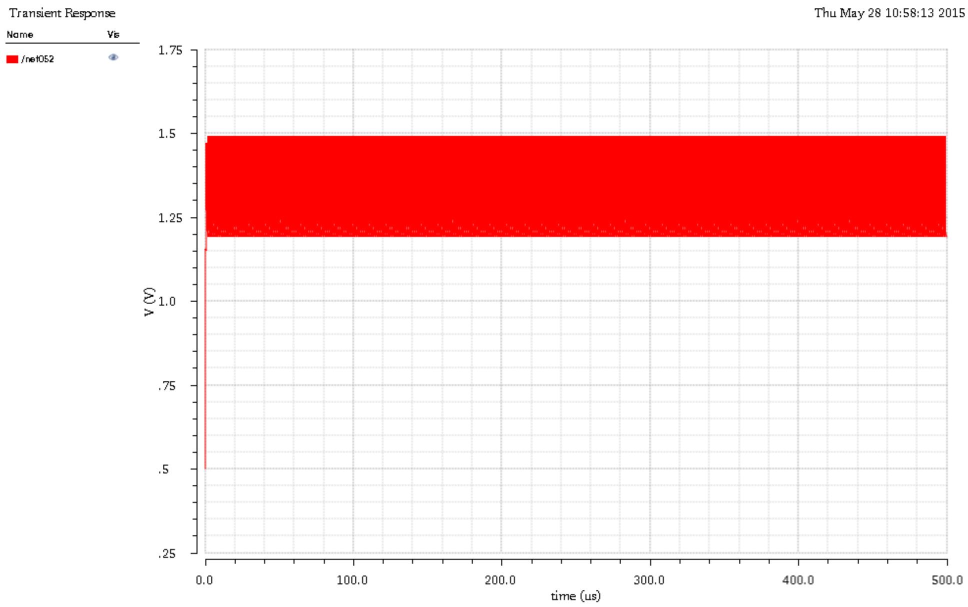


Figure 6-30

b. f=10MHz

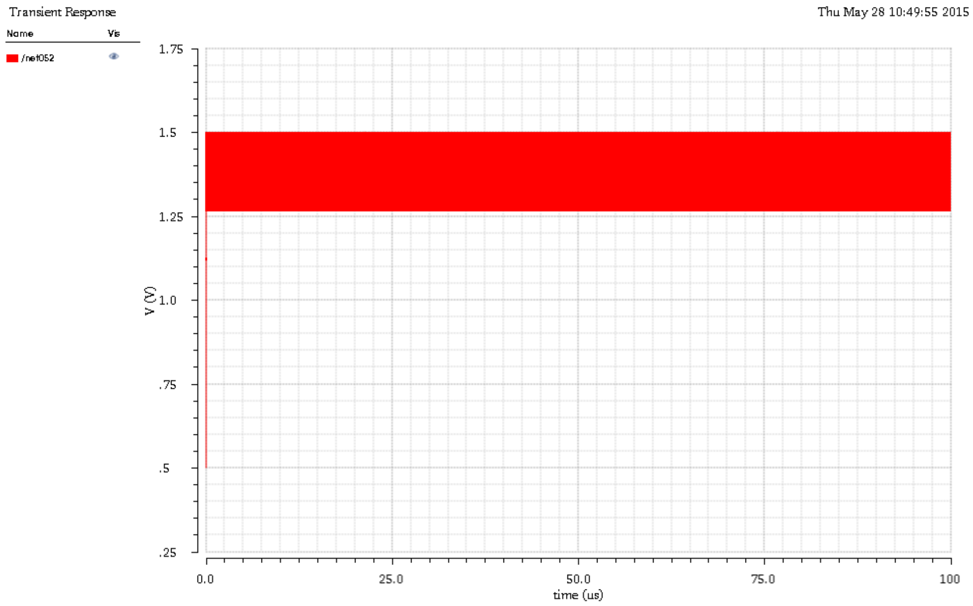


Figure 6-31

c. f=100MHz

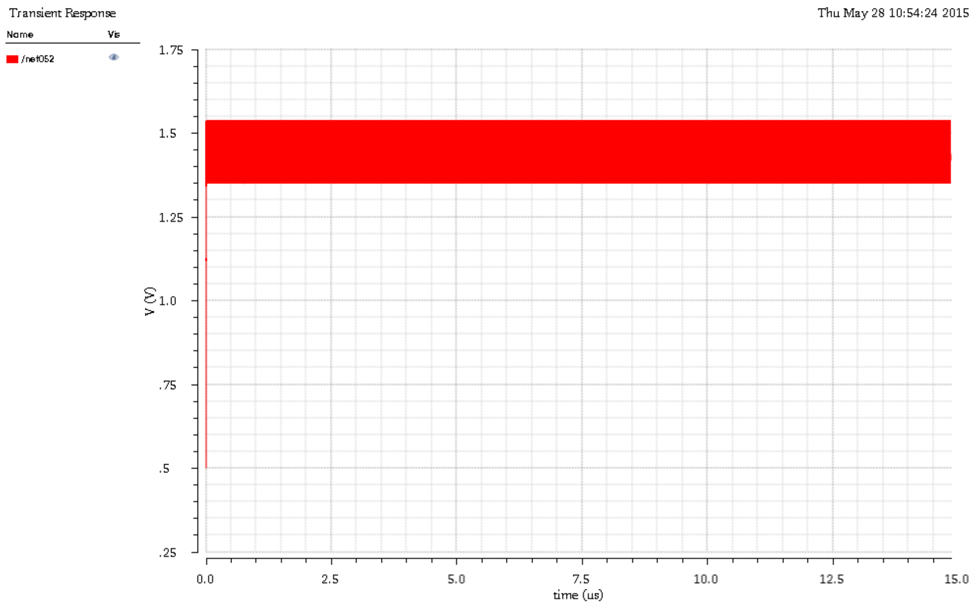


Figure 6-32

The voltage reached is lower than with the Dickson charge pump but it is because of the number of stages. Also we can observe the oscillation is greater than in the other charge pump.

Minimum voltage: *120mV*

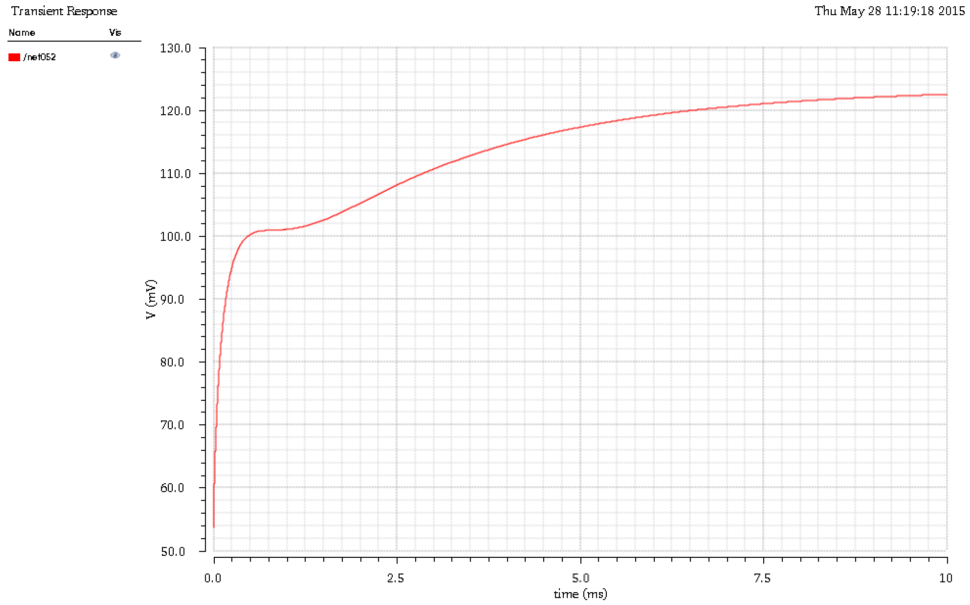


Figure 6-33

6.2.3 Comparison

	Frequency	400 kHz	10 MHz	100 MHz
Output voltage [V]	Dickson	2,7	2,8	2,8
	Cross-coupled	1,3	1,35	1,4

Table 6-5

First of all, as it can be observed in the circuits, it must be said that these two charge pumps do not have the same amount of stages. Hence, even if the Dickson's charge pump gives a higher output voltage it must be kept in mind that it is after a four stage charge pump. On the other hand, it is true that it can work with a lower input voltage than the Cross-coupled one. Based on these results I believe the Cross-coupled would be a good option. However, a further study considering more stages should be done as the output voltage regarding one only stage is not high enough.

6.3 Complete circuit

After having studied various possibilities for each circuit: the oscillator and the charge pump, we ought to put them together. As in real life they will be working together, they must also be studied this way in order to examine how they complement each other and if they respond the same way and give the same results as separately.

Here are the different circuits that were studied.

1) Ring oscillator + Dickson charge pump

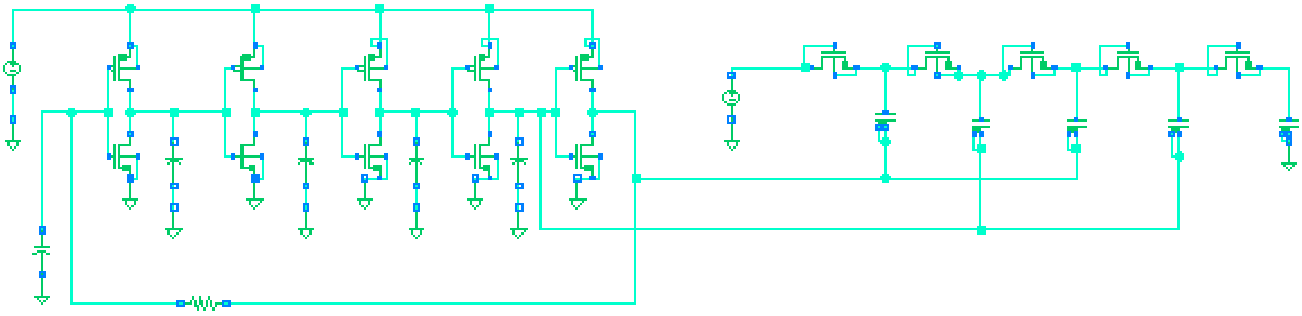


Figure 6-34

2) Astable oscillator + Dickon charge pump

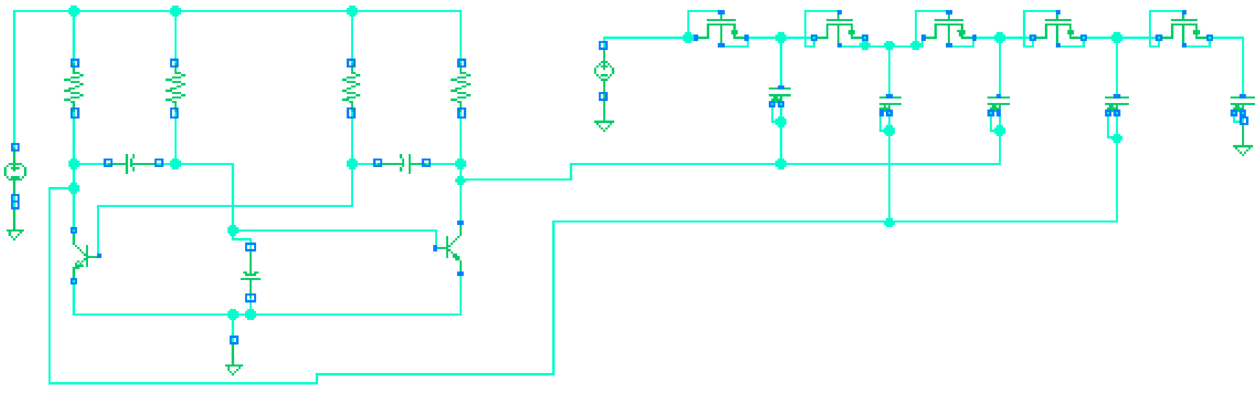


Figure 6-35

3) Ring oscillator + Cross-coupled charge pump

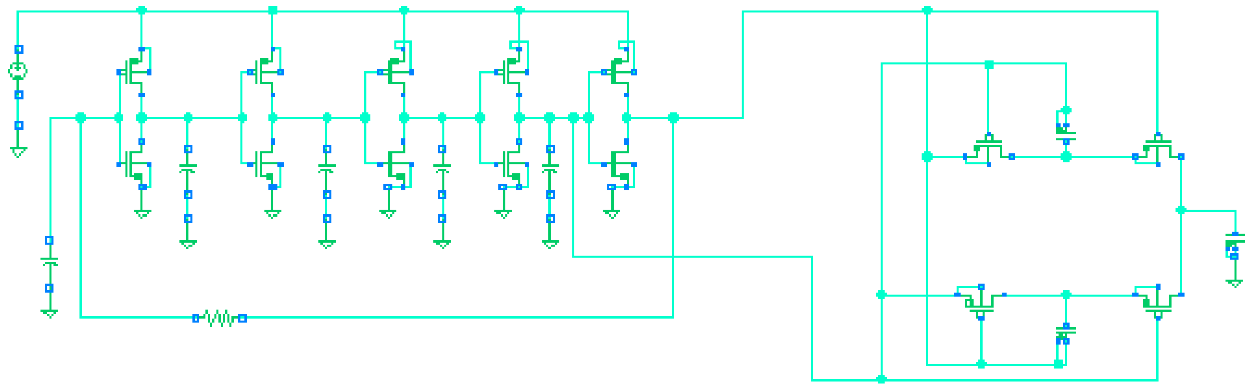


Figure 6-36

4) Astable oscillator + Cross-coupled charge pump

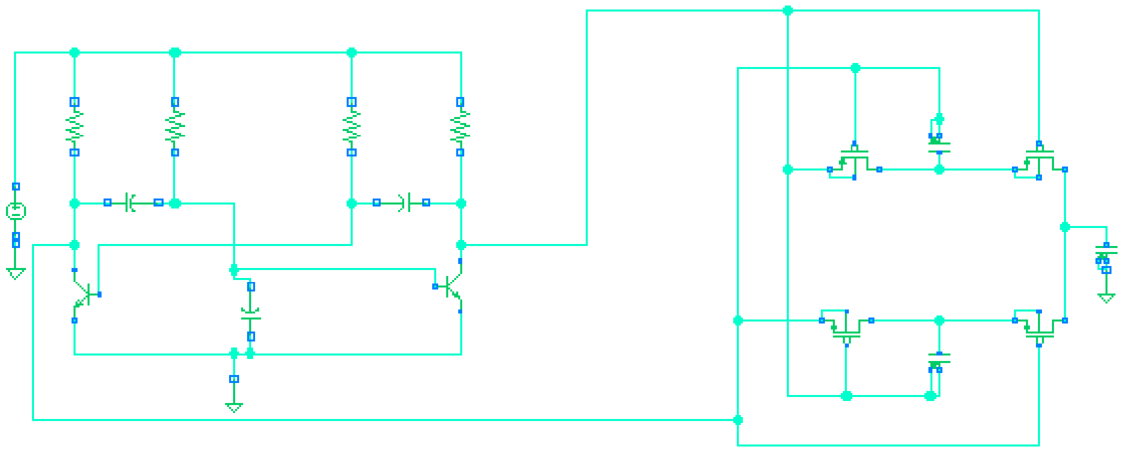


Figure 6-37

a. f=400 kHz

	1	2	3	4*
Output [V]	2,5	2,4	1,15	1,2
Max Power out [W]	7,5 · 10^{-8}	1,5 · 10^{-6}	4,3 · 10^{-8}	7,5 · 10^{-6}

Table 6-6

b. f=10 MHz

	1	2[2]	3	4[2,3]
Output [V]	2,68	1,5	1,2	1,2
Max Power out [W]	$2 \cdot 10^{-7}$	$2 \cdot 10^{-7}$	$3{,}8 \cdot 10^{-6}$	$3 \cdot 10^{-5}$

Table 6-7

c. f=100 MHz

	1	2[3]	3	4[3]
Output [V]	2,68	2	1,25	1,2
Max Power out [W]	$7{,}5 \cdot 10^{-7}$	$6 \cdot 10^{-8}$	$7{,}5 \cdot 10^{-6}$	$2 \cdot 10^{-6}$

Table 6-8

Even if the type of oscillator chosen was quite clear it was necessary to do a study of all four possibilities to compare the final results.

As it has already been mentioned the output voltage accomplished in those options that enclose a Dickson charge pump are higher. However, this is because more stages were used in this circuit and therefore, I see more potential in the cross-coupled options. Nevertheless, further study of it must be done so this can be truly said.

The possible options would be 3 or 4 as they have a cross-coupled charge pump and also they have a higher output power. However, since the astable does not fulfill the frequency requirements option 3 seems the more feasible. It must be mentioned though, that the output voltage is still low regarding the input one. However, as it has already been stated, the charge pump still needs to be improved so the circuit altogether gives its best performance.

7 Solution proposal performance

As it has been mentioned, the chosen option is the one which combines the ring oscillator and the cross-coupled charge pump due to the reasons previously exposed.

[2] *Initial values of astable components were slightly modified. See appendix table I-1 and table I-2.*
[3] *Values for f= 50MHz as the astable does not achieve 100MHz.*

Here there is part of the results obtained with this combination.

f = 400 kHz

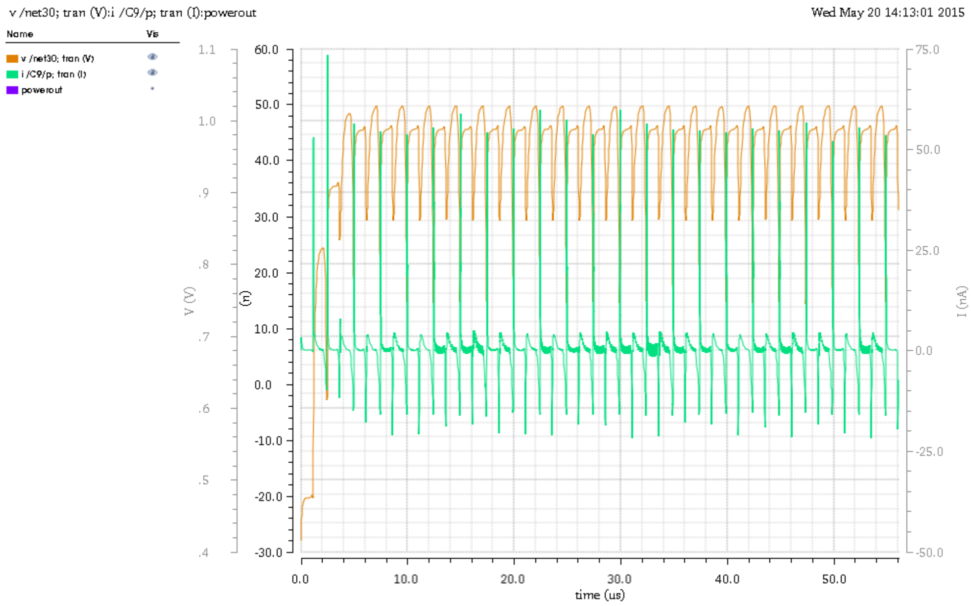


Figure 7-1 Output voltage and intensity

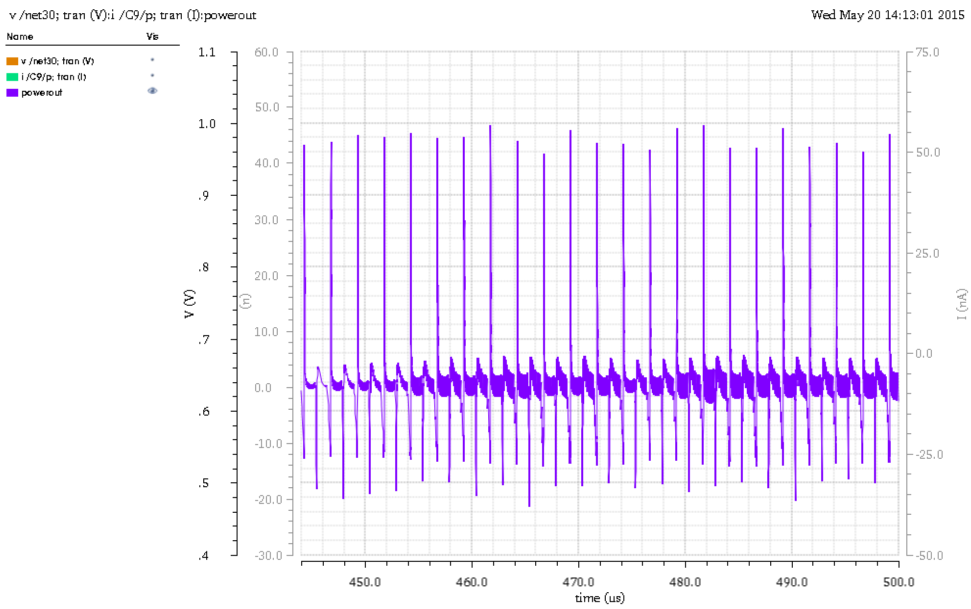


Figure 7-2 Output power

f = 10MHz

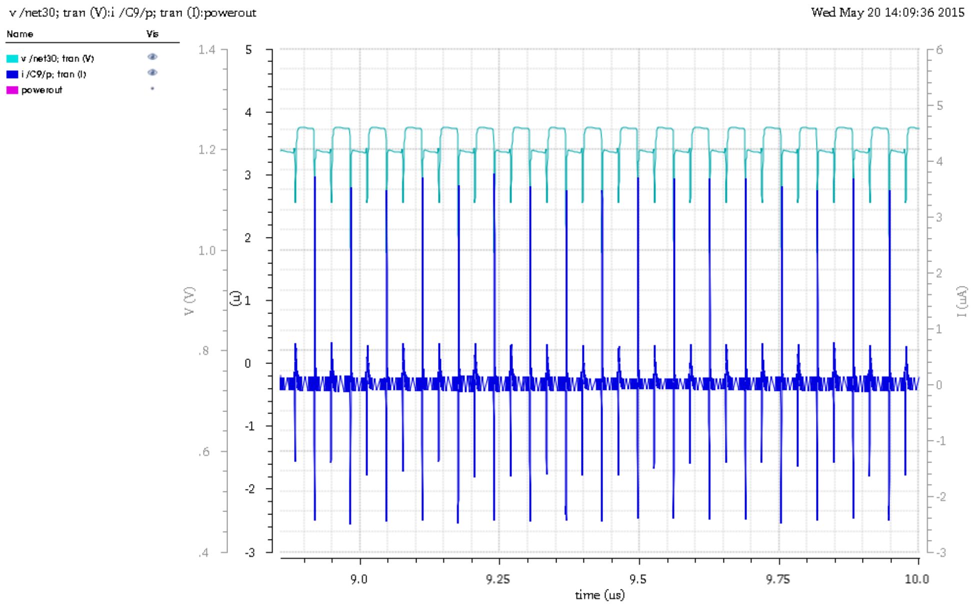


Figure 7-3 Output voltage and intensity

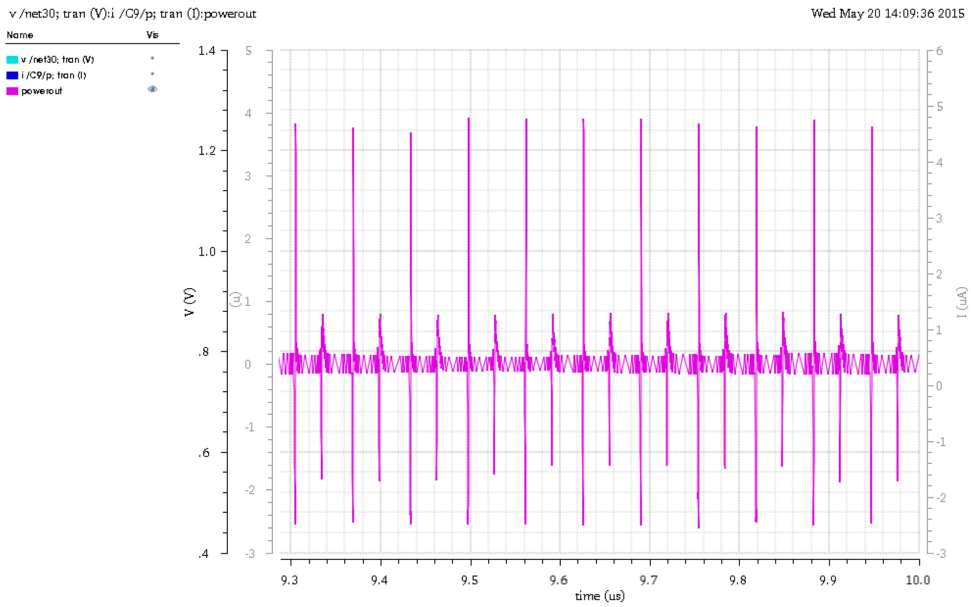


Figure 7-4 Output power

f = 100MHz

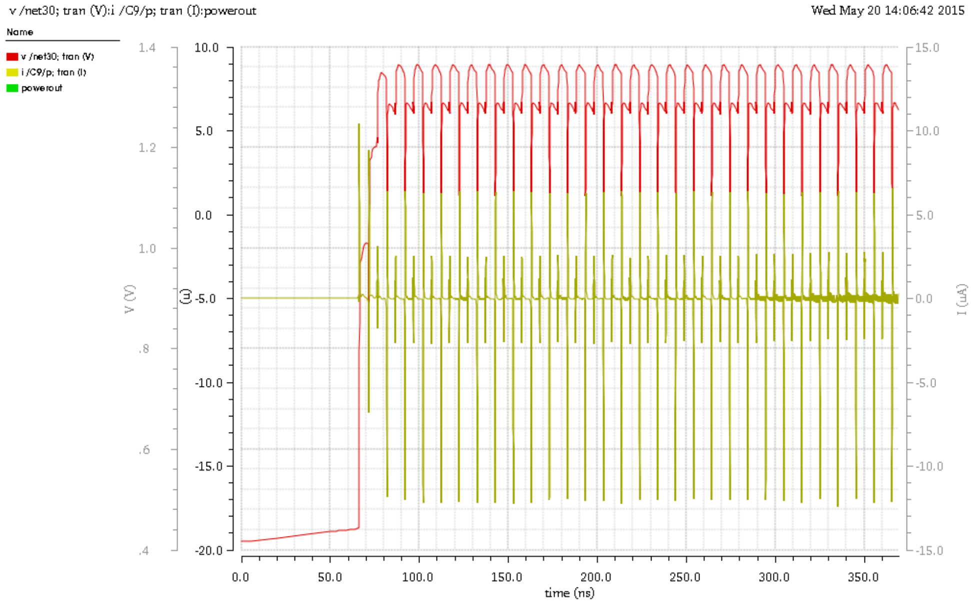


Figure 7-5 Output power and intensity

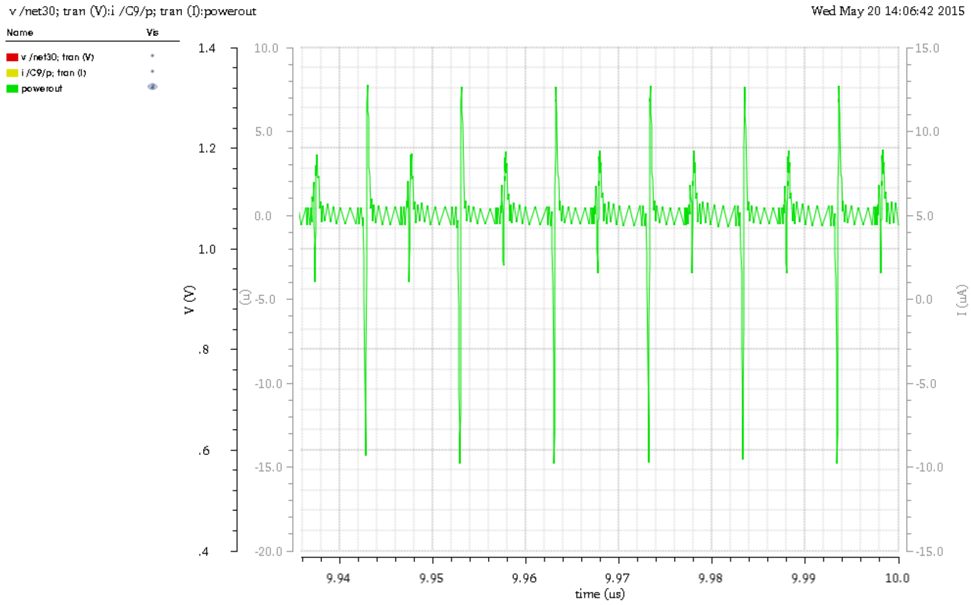
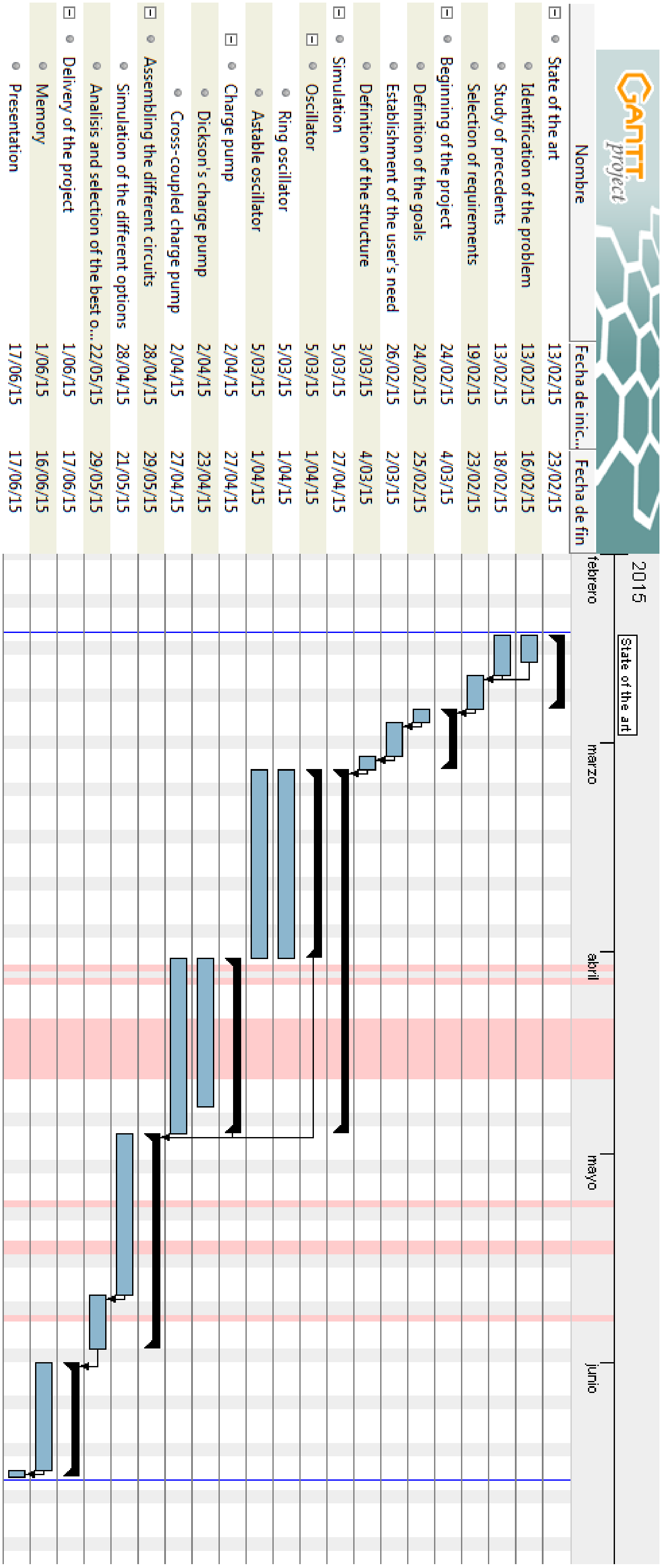


Figure 7-6 Output power

In the lasts figures we can see the output voltage, intensity and power for the three different frequencies of the circuit that was finally chosen. I would like to stand out the peaks we can observe in the intensity and in the power cause by the change of state of the oscillator.

8 Development time

In order to organise our project in time a Gantt diagram was constructed. This kind of diagram offers a very intuitive view of the duration of the project and gives a reference when it comes to determinate if there is an alarming delay in any task. Also, it can help quantify the impact that this delay can cause in the duration of the entire project.


GANTT project
Nombre
Fecha de inic...
Fecha de fin
State of the art 13/02/15 23/02/15
Identification of the problem 13/02/15 16/02/15
Study of precedents 13/02/15 18/02/15
Selection of requirements 19/02/15 23/02/15
Beginning of the project 24/02/15 4/03/15
Definition of the goals 24/02/15 25/02/15
Establishment of the user's need 26/02/15 2/03/15
Definition of the structure 3/03/15 4/03/15
Simulation 5/03/15 27/04/15
Oscillator 5/03/15 1/04/15
Ring oscillator 5/03/15 1/04/15
Astable oscillator 5/03/15 1/04/15
Charge pump 2/04/15 27/04/15
Dickson's charge pump 2/04/15 23/04/15
Cross-coupled charge pump 2/04/15 27/04/15
Assembling the different circuits 28/04/15 29/05/15
Simulation of the different options 28/04/15 21/05/15
Analisis and selection of the best o... 22/05/15 29/05/15
Delivery of the project 1/06/15 17/06/15
Memory 1/06/15 16/06/15
Presentation 17/06/15 17/06/15
2015
febrero
marzo
abril
mayo
junio
State of the art

9 Points of review

Even if the recuperation of electromagnetic energy is not a brand new idea its implementation is still not very widely spread. This is why I feel it is only natural that a project of this kind is far away from being completed. There is plenty of investigation that still needs to be done and many ways that still need to be explored. This is the reason why, when a project like this is finished, we ought not to focus on the results only, but also on those characteristics which need further study.

In this case, a first study of different circuits and how they work together was done. We used the basic circuits and only one combination of stages was regarded. Nevertheless, many improvements exist for each of them and stages can be modified. Hence, there are many possibilities which can be considered in order to make the most of this circuit. What this project has given us is an idea of how do these circuits respond so we can start from the circuits who gave the best results.

Having said that, what needs to be done first is study how many stages should the cross-coupled charge pump have to at least be able to double the initial voltage. Also, an improved charge pump can be used to increase its efficiency and performance. A different number of stages can also be tested in the ring oscillator if they end up being odd. What should be done next is lower the entering voltage to see if the whole circuit still works and until which voltage it does so it can be established in what circumstances this product will be useful. Finally, a way of storing the energy that is recuperated should be considered so it can be taken into account when placing a component at the end of the charge pump.

10 Conclusion and future development

'*One day of extra energy use from electric kettles is enough to light all the streetlights in London for a night.'* [8]

'Certainly conservation and energy efficiency has a role to play, as does the continuing exploration of renewable resources.' [9]

In the recent years the demand for energy has raised incredibly. Besides our main energy source is drastically running out. It is time for a change and we really need it because of two main reasons. The first one is the drop of the exhaustion of fossil fuels and the second one, climate change. In my personal opinion the search of a clean and powerful energy is the most crucial challenge nowadays.

We need to be aware that fossil fuels will not last forever and we cannot continue using this kind of energy because of all the negative effects it involves. In fact, we emit 26 billion tons of CO_2 per year and we definitely need to reduce down to zero the amount of CO_2 we emit if we want to avoid the continuous rise of temperature. This is because a rise in temperature will consequently lead to many catastrophes as ecosystems cannot adjust quickly enough and they collapse. We need to come up with a type of energy with unbelievable scale and reliability. I believe that by deeply exploring the renewable energies such as wind energy, solar photovoltaic or solar thermal we would come up with a perfectly valuable solution. In fact, throughout history we have had many peaks of different energy sources and, as I see it, it is time for the use renewables to continue increasing and to become the most used type of energy.

I feel we should really focus on exploring the different alternatives ahead of us in order to find one which suits us. We need to do that and we need to do it in a pretty tight timeline because we are working against the clock. It is true that there is a lot of uncertainty ahead of us but I believe that if we work hard on that, we will eventually discover a great solution to what I think is one of our biggest problems.

I consider RF energy harvesting a captivating idea. Even if it is not a new idea I believe it has future because it is a way of not letting energy that is already generated to go to waste. Thereupon, it is an idea that can be always applied. Undoubtedly, this is not a solution for the clean generation of energy because the power we obtain is minimal but I am convinced that if we could apply it to our daily life we would be saving an unexpected amount of energy. If we stop to think about all the little devices we use day-to-day there is plenty of them and I believe we could harvest energy in order to make them work or even use some of them to recharge the others.

This is the idea this project pursues. It studies some circuits in order to give an idea of which way to go. I am certain this will be an used method in the future. When choosing this project what caught my attention was not only the electronic part of it but also the future ahead of it. I strongly believe that by implementing this idea we will be producing a global impact on society and maybe this would be the beginning of that change I have mentioned before. This is what, in my opinion, gives an added value to this project.

11 Bibliography

11.1 References

[1] Sebastian Antoni, Extreme Tech (2013). *German student creates electromagnetic harvester that gathers free electricity from thin air.* [http://www.extremetech.com/extreme/148247-german-student-creates-electromagnetic-harvester-that-gathers-free-electricity-from-thin-air, 12/03/2015]

[2] Duncan Graham-Rowe, MIT Technology review (2009). *Wireless Power Harvesting for cell phones*. [http://www.technologyreview.com/news/413744/wireless-power-harvesting-for-cell-phones/, 12/03/2015]

[3] Wikipedia. Ring Oscillator. [en.wikipedia.org/wiki/Ring_oscillator, 8/04/2015]

[4] Electronics tutorials. Astable Multivibrator. [http://www.electronics-tutorials.ws/waveforms/astable.html, 8/04/2015]

[5] Learn about electronics. BJT Astable Multivibrators. [http://www.learnabout-electronics.org/Oscillators/osc41.php, 8/04/2015]

[6] Edward S. Rogers, *"Charge pumps: An Overwiew*".

[7] Hanfeng Wang. "*Switched-Capacitor Voltage Doubler Design Using 0.5µm Technology", 2014*

[8] Leyla Acaroglu quote. TED talk 2013.

[9] Keith Poston quote.

11.2 Complementary bibliography

Mandal, M.K. & Sarkar, B.C."*Ring oscillators: Characteristics and applications*"

Vratislav MICHAL*. "On the Low-power Design, Stability Improvement and Frequency Estimation of the CMOS Ring Oscillator"*

Francisco R. Villatoro blog (2013). *Un oscilador en anillo con transistors de grafeno.* [http://francis.naukas.com/2013/04/24/un-oscilador-en-anillo-con-transistores-de-grafeno/, 26/02/2015]

Electrónica completa (2010) *Fabricación de dispositivos con compuertas lógicas* [http://electronicacompleta.com/lecciones/fabricacion-de-dispositivos-con-compuertas-logicas/, 26/02/1015]

Universidad Computense de Madrid. Facultad de físicas. *Electrónica analógica: Osciladores* [cv3.sim.ucm.es/access/content/group/portal-uatducma-43/webs/material_original/apuntes/PDF/10_Osciladores.pdf, 03/03/2015]

Sinusoidal and non-sinusoidal oscillators [http://es.slideshare.net/mhmdenab/ch-65, 21/05/2015]

Aamna Anil and Ravi Kumar Sharma *"A high efficiency charge pump for low* voltage devices"

I. Appendix

A. Oscillator

1. Ring oscillator

- f=400 kHz

Input voltage and intensity

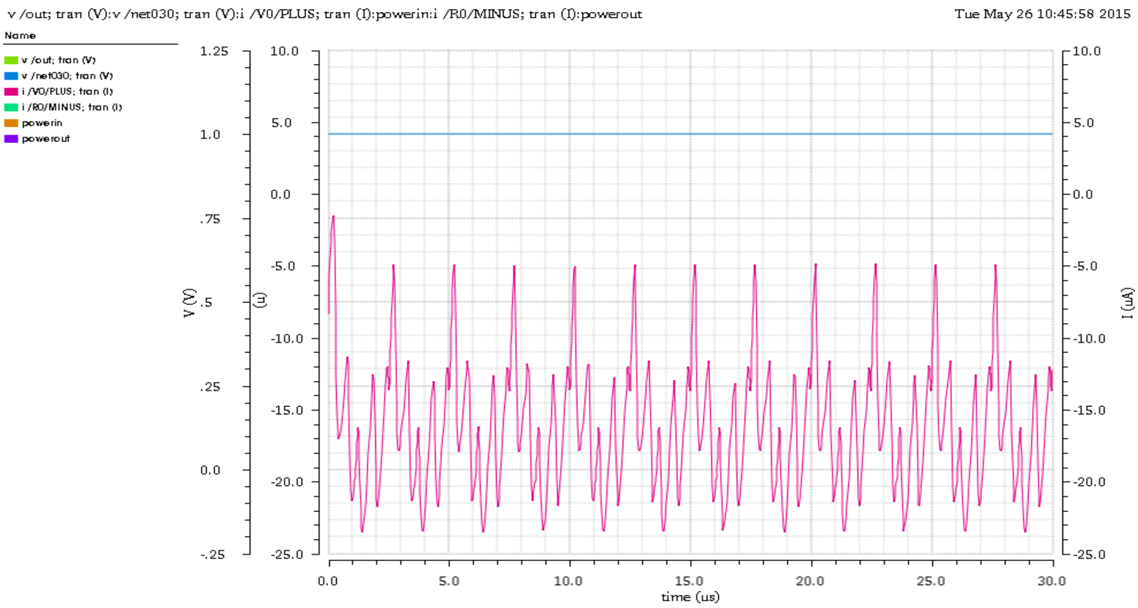


Figure I-1

- f= 10MHz

Input voltage and current

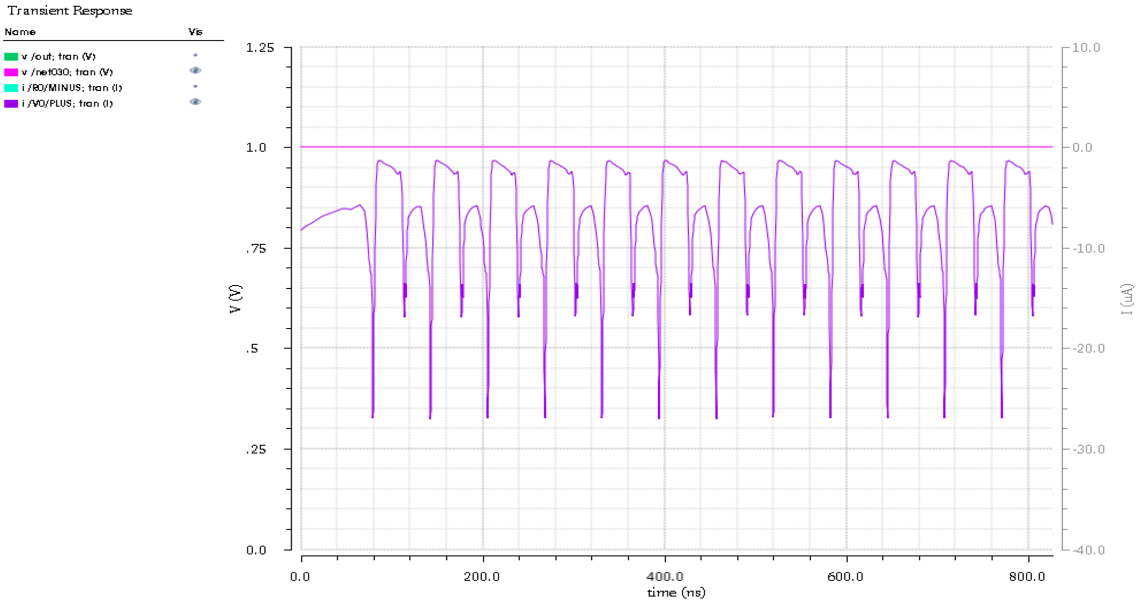


Figure I-2

- f=100MHz

Input voltage and intensity

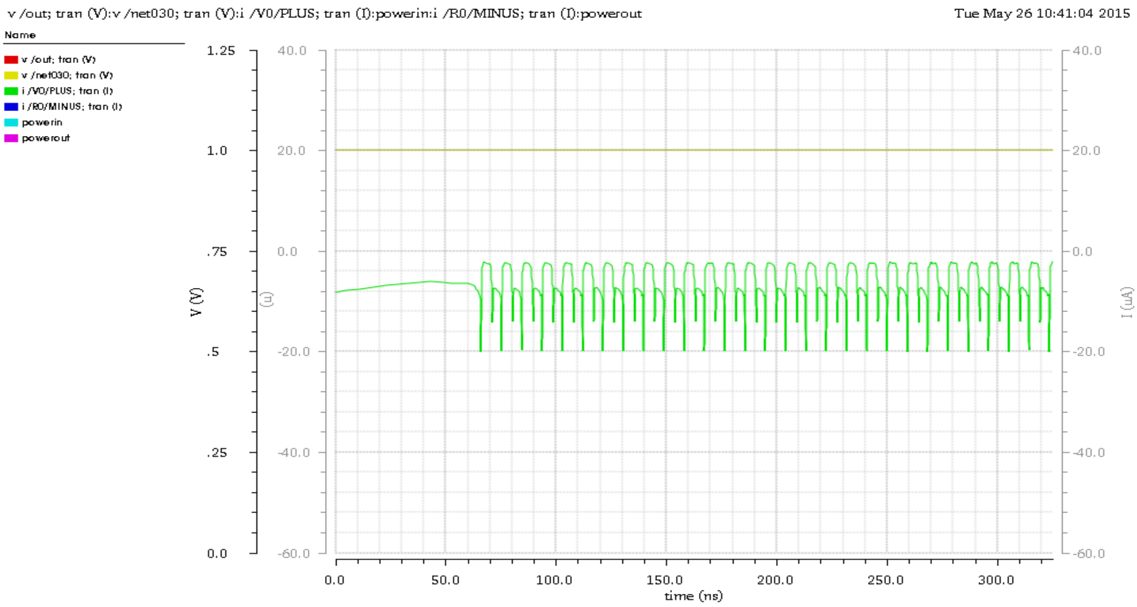


Figure I-3

2. Astable oscillator

- f=400 kHz

Input voltage and intensity

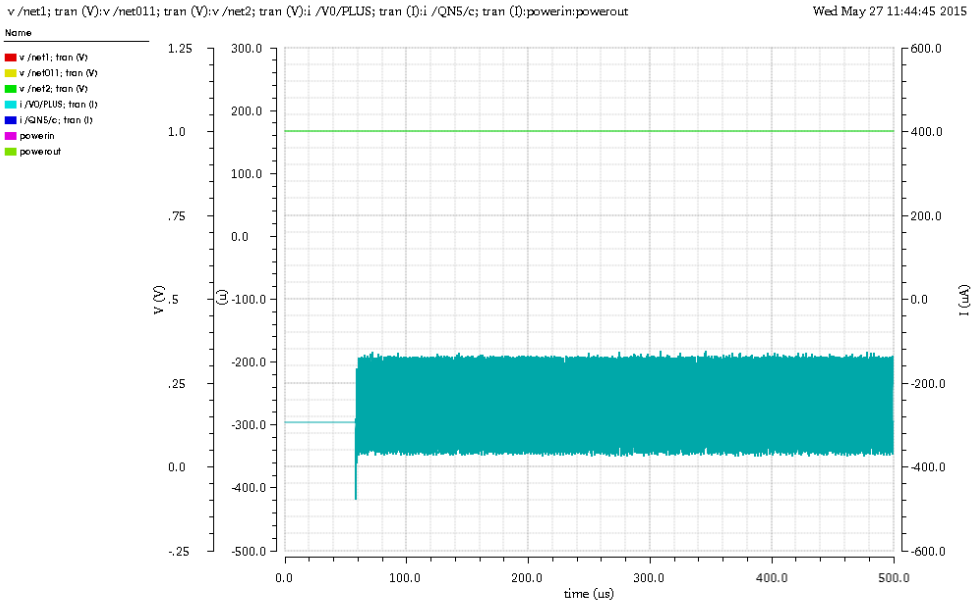


Figure I-4

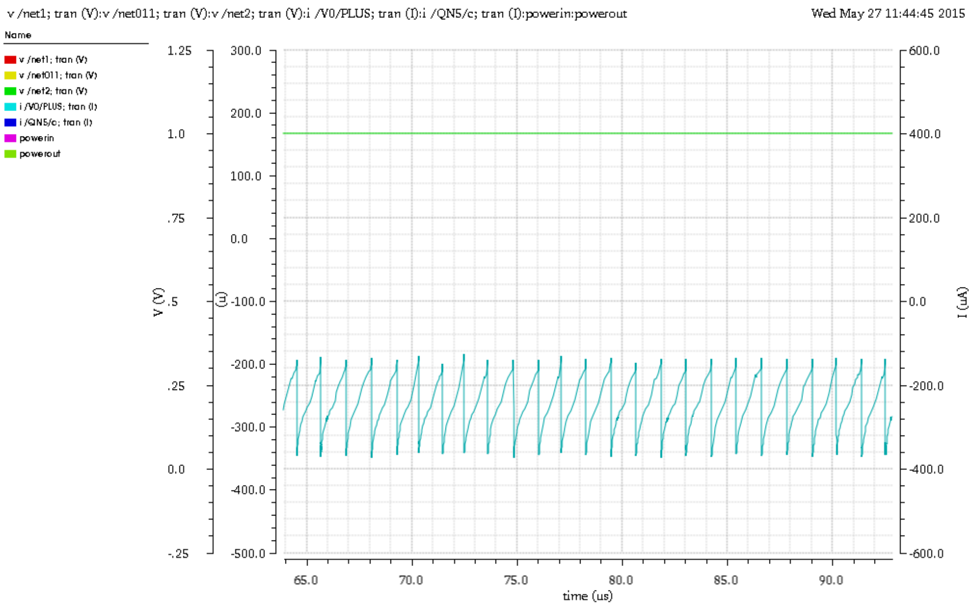


Figure I-5

Output voltage and intensity

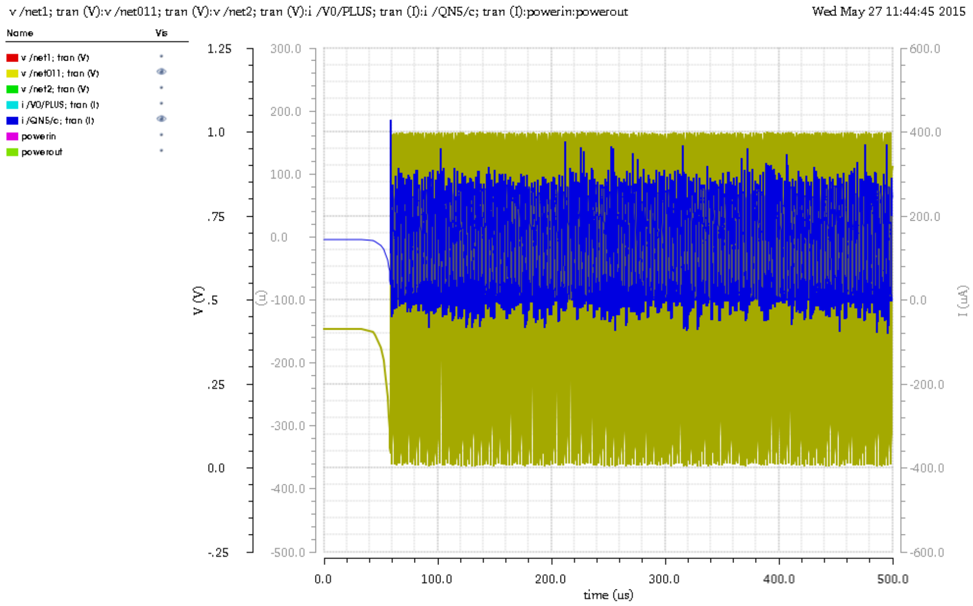


Figure I-6

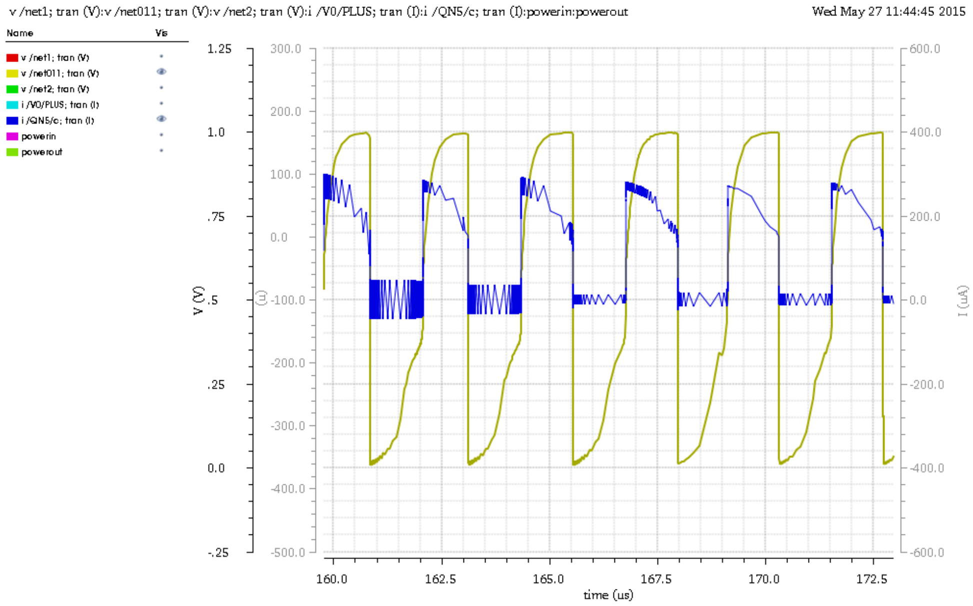


Figure I-7

Input power

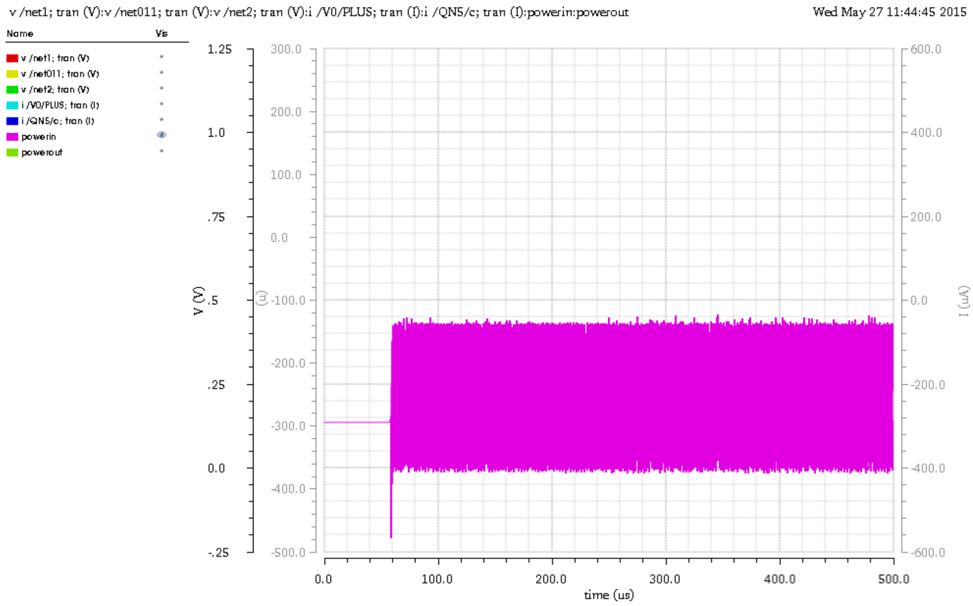


Figure I-8

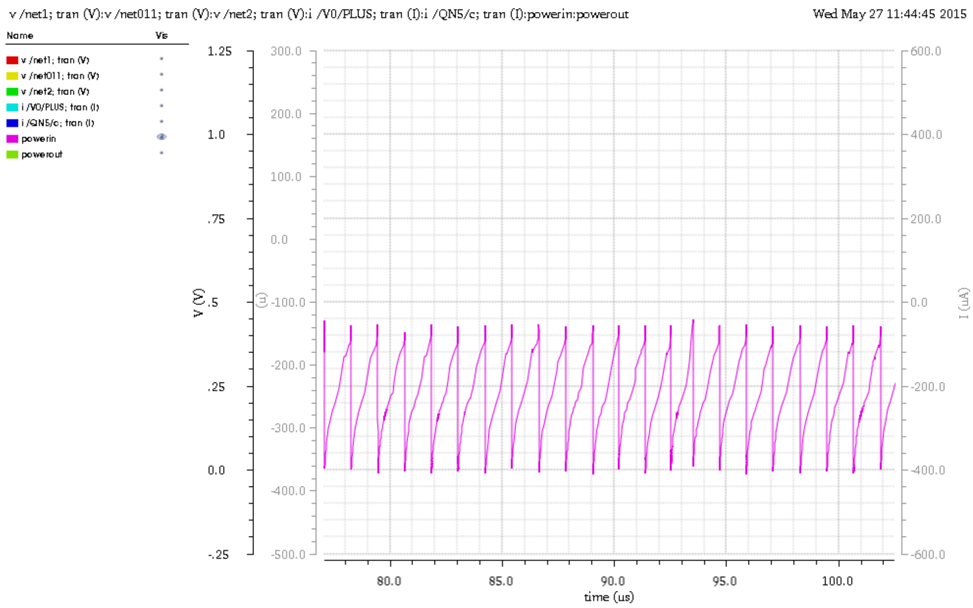


Figure I-9

Output power

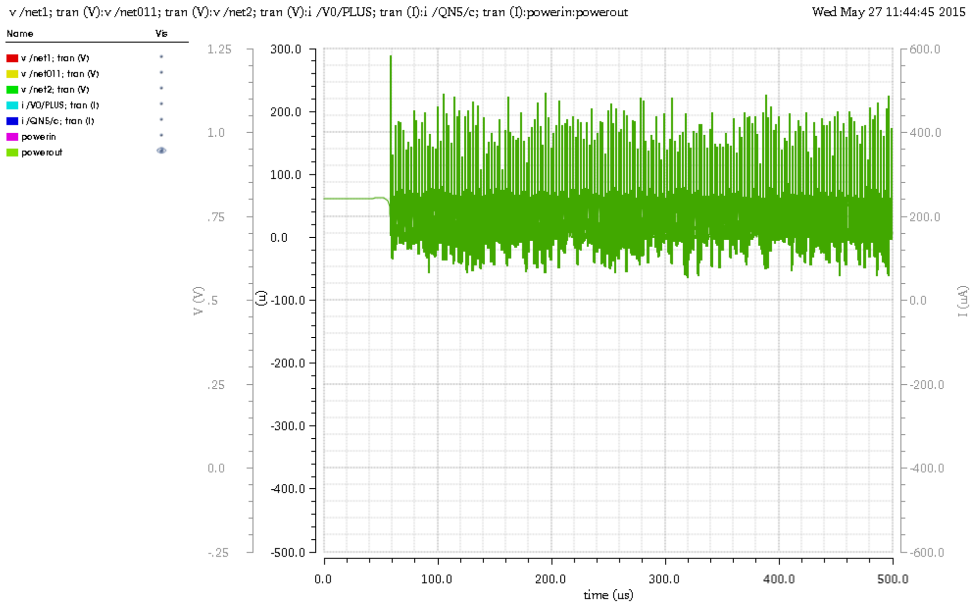


Figure I-10

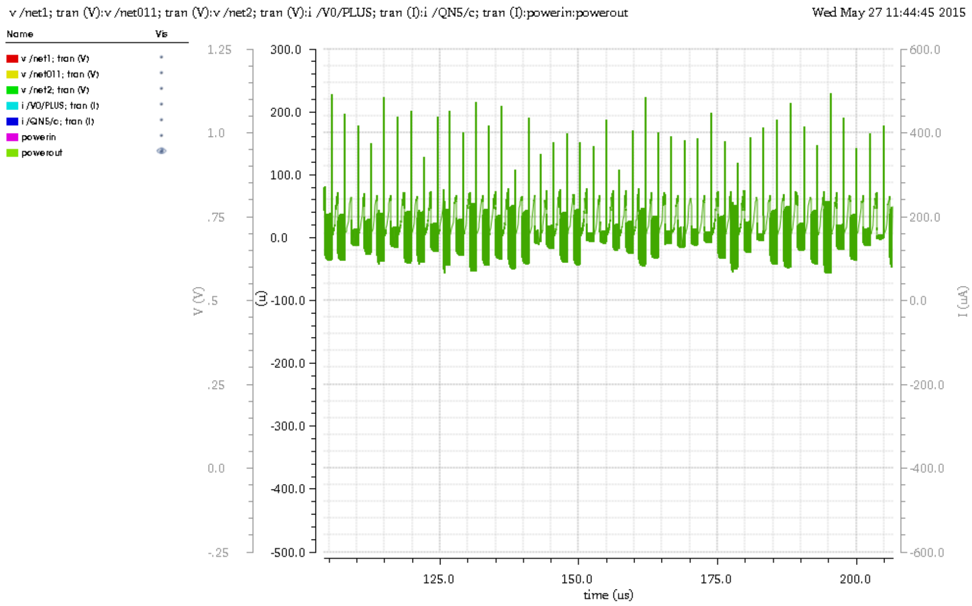


Figure I-11

- f= 10MHz

Input voltage and intensity

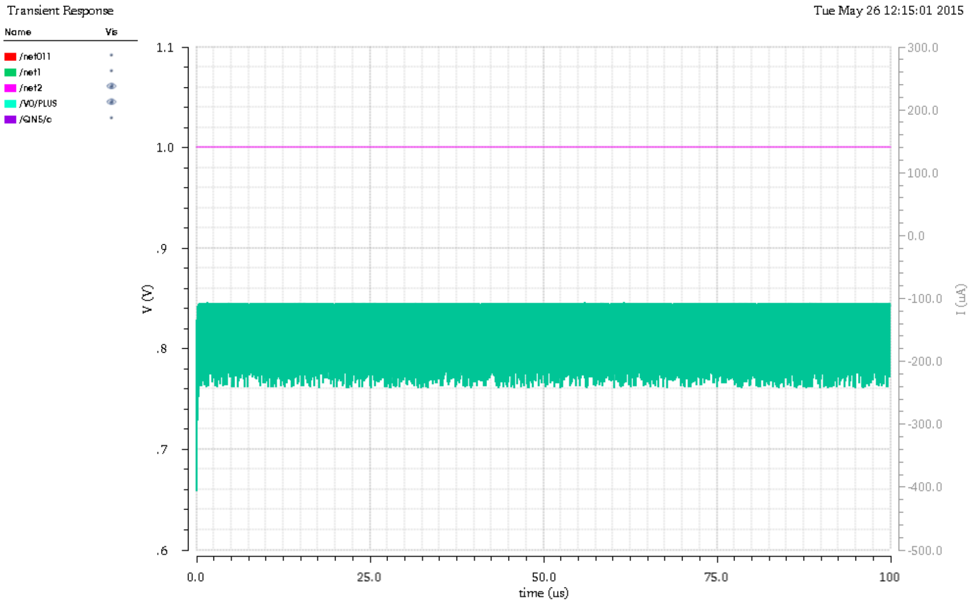


Figure I-12

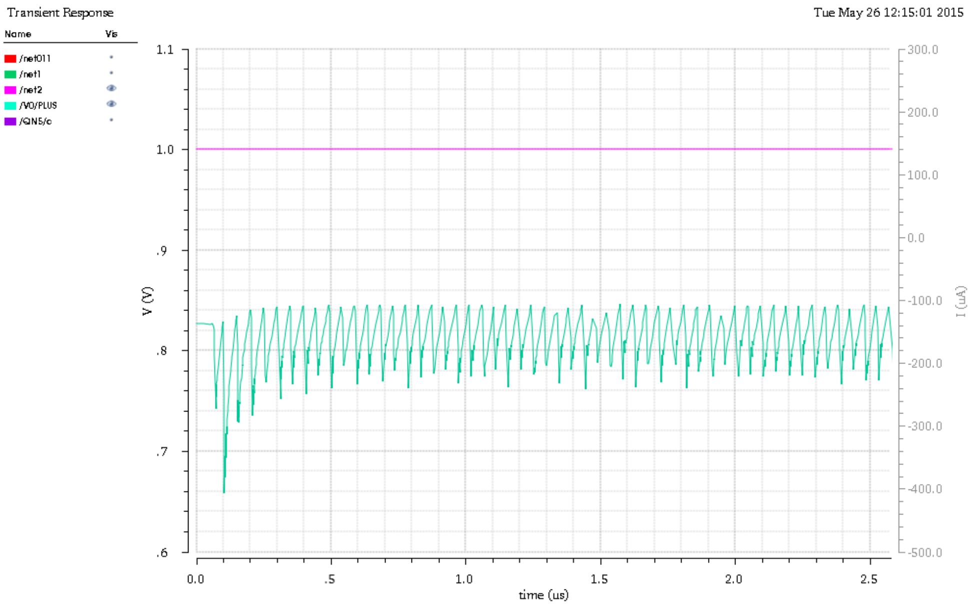


Figure I-13

Output voltage and intensity

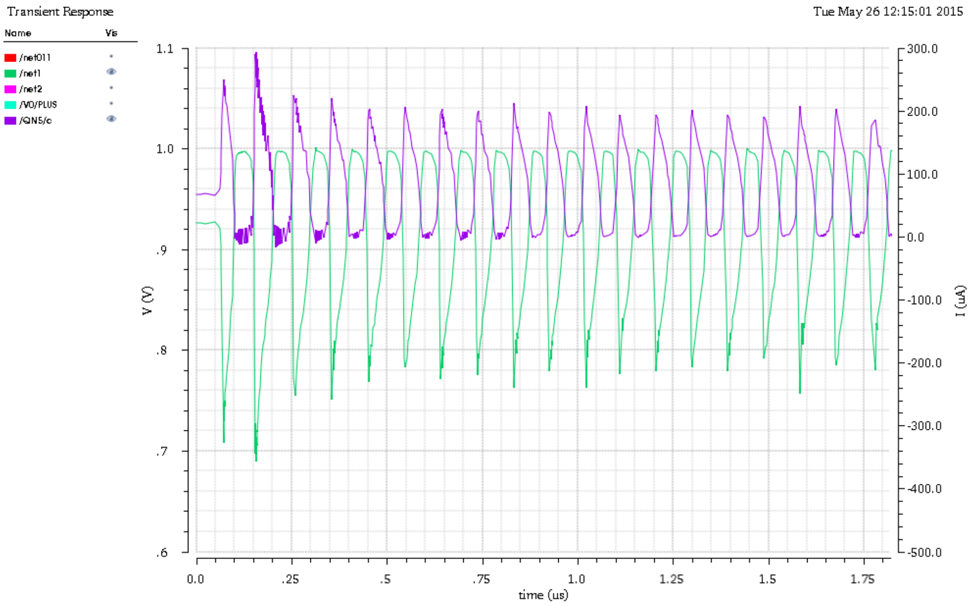


Figure I-14

Input power

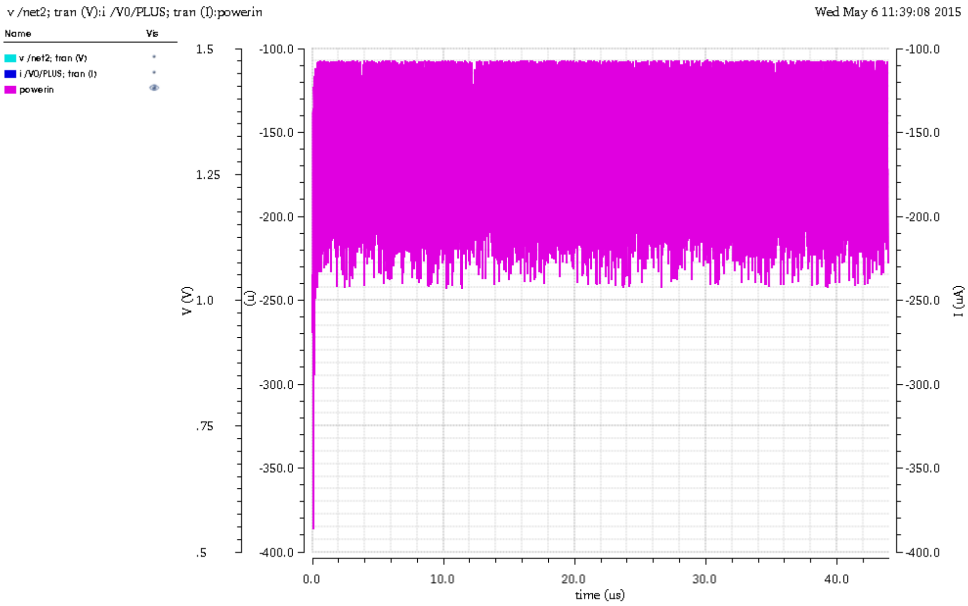


Figure I-15

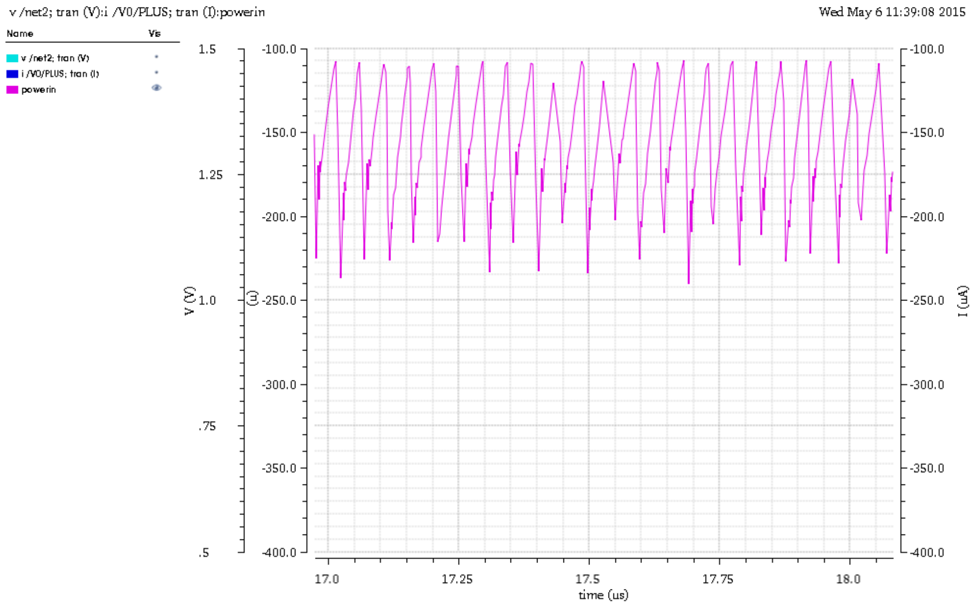


Figure I-16

Output power

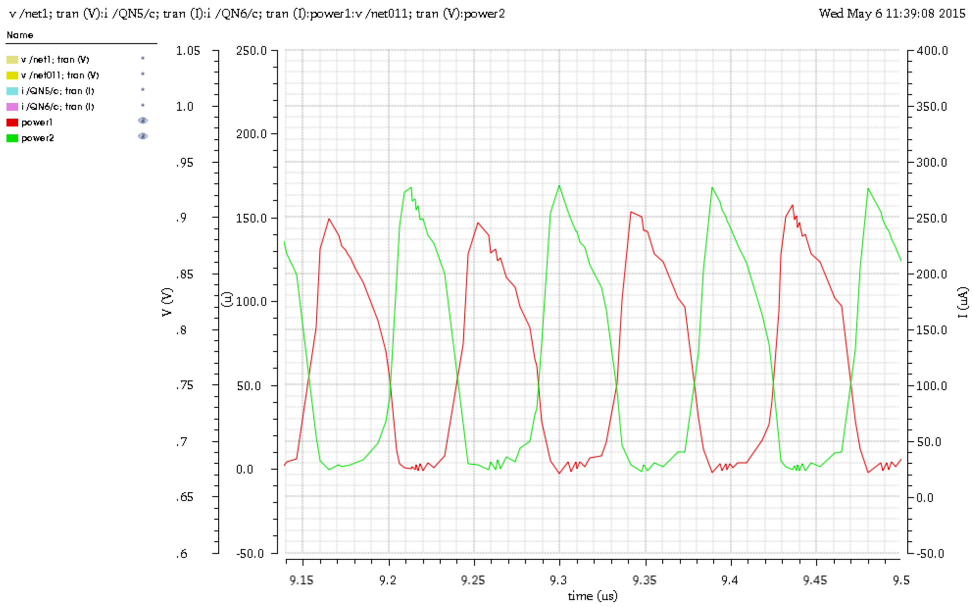


Figure I-17

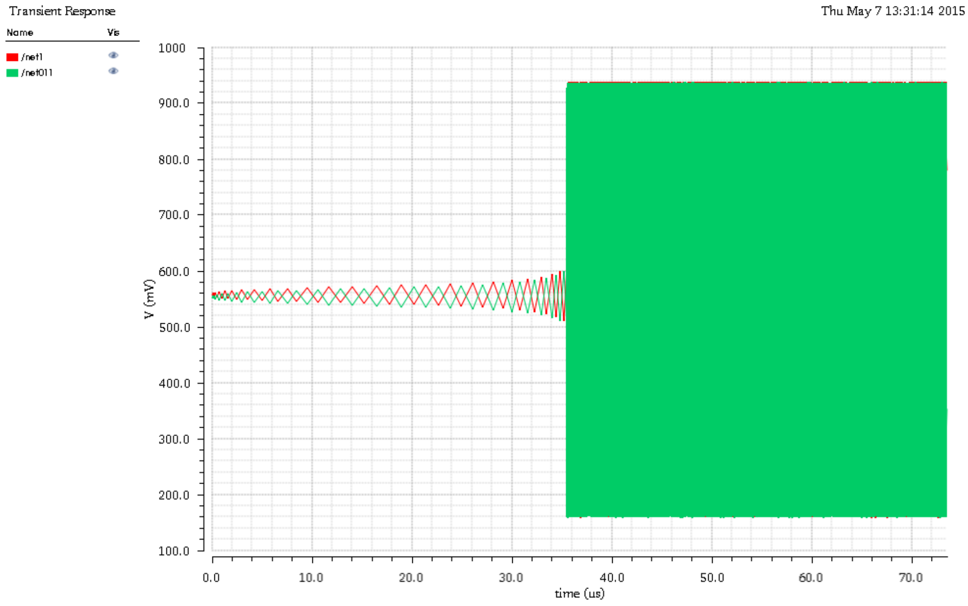


Figure I-18

- f = 50MHz

Output

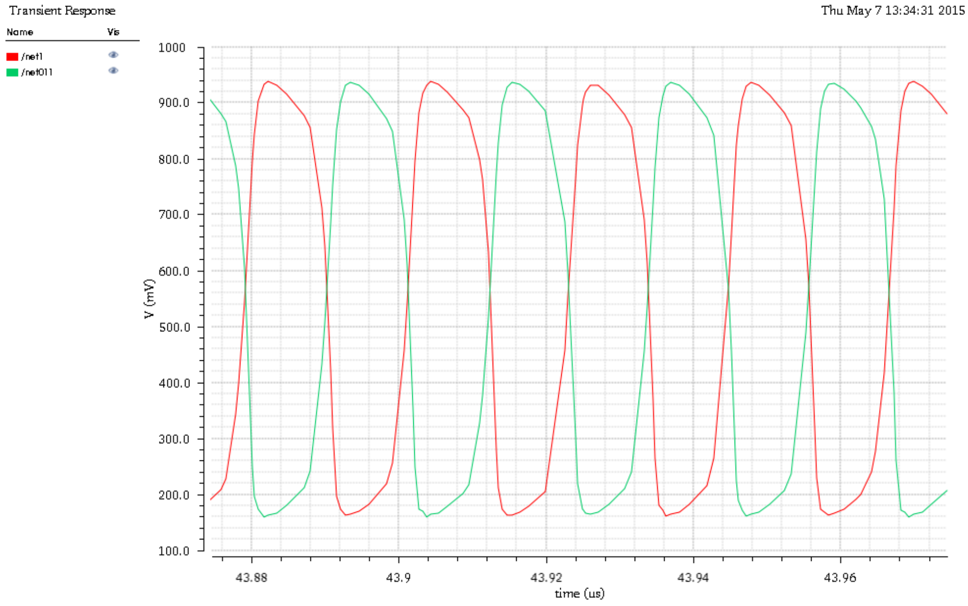


Figure I-19

Input power

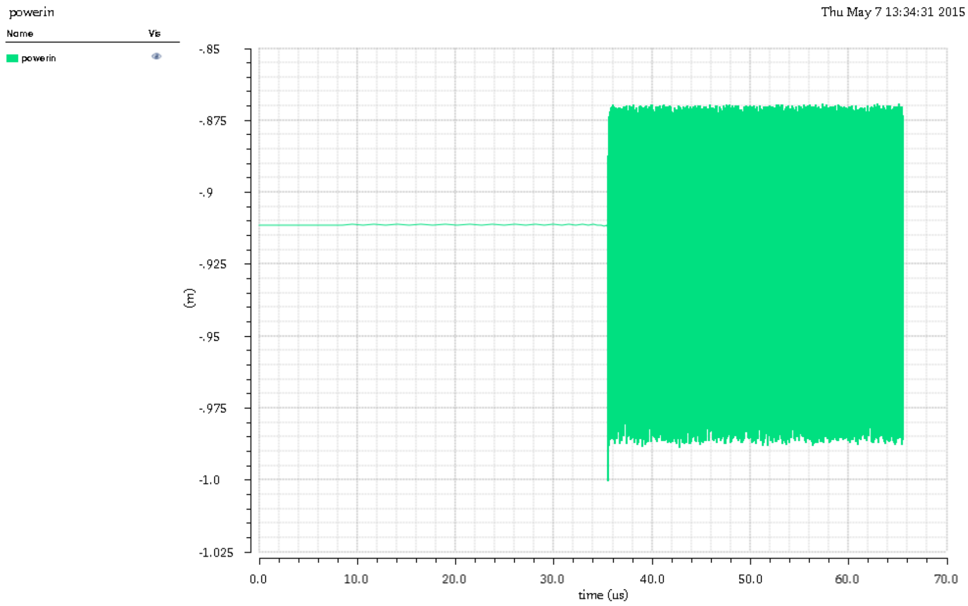


Figure I-20

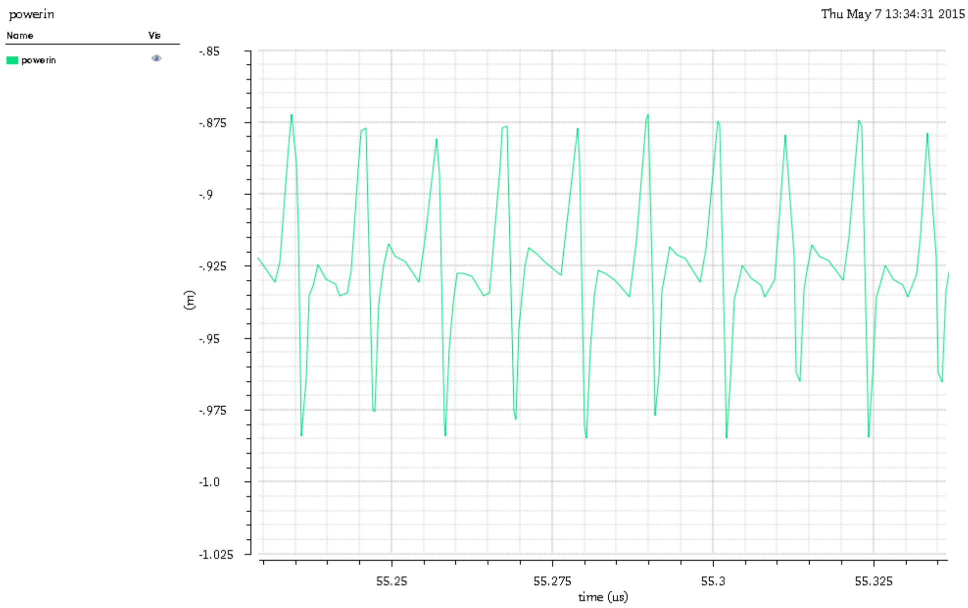


Figure I-21

Output power

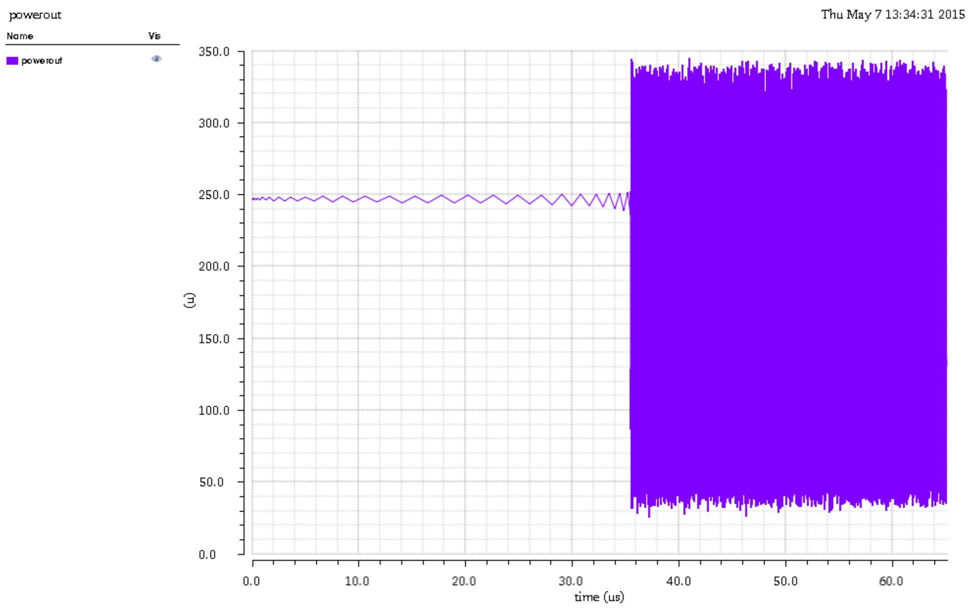


Figure I-22

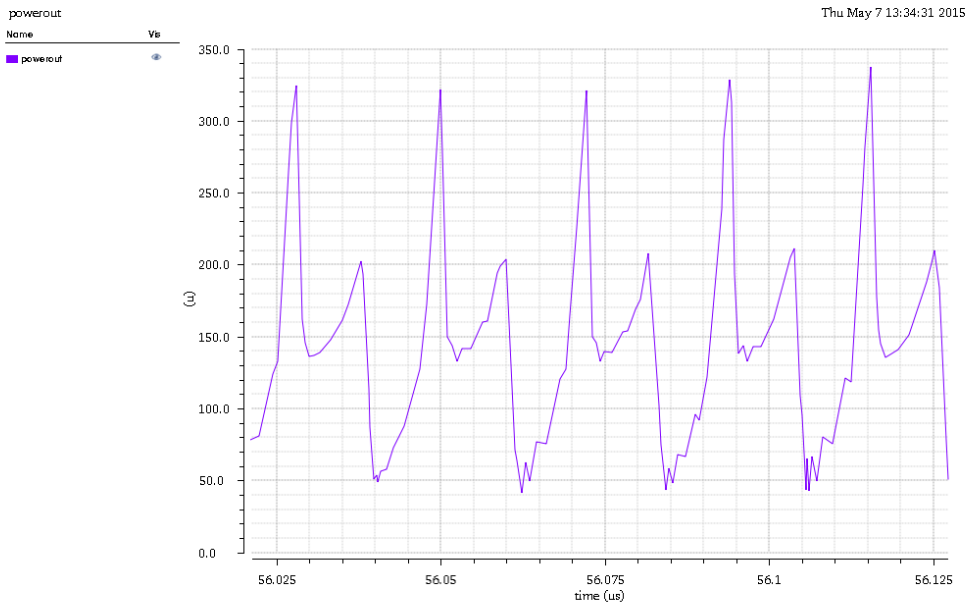


Figure I-23

B. Charge pump

1. Dickson charge pump

- f=400 kHz

Output

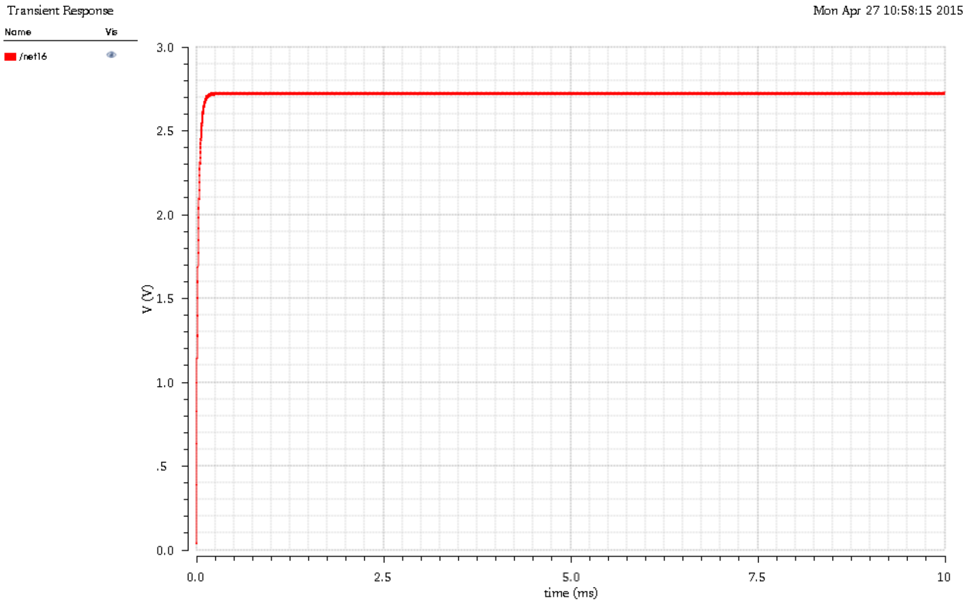


Figure I-24

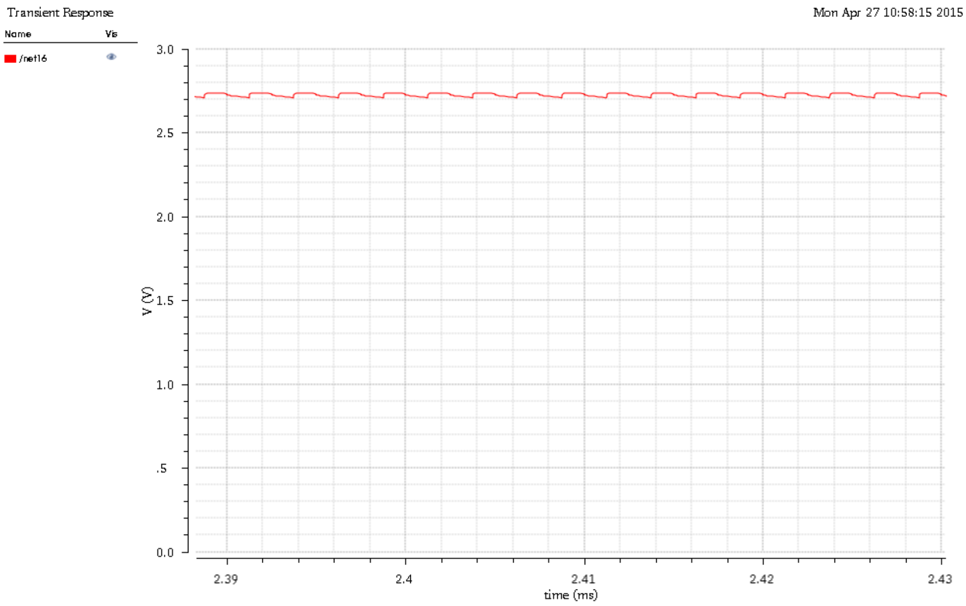


Figure I-25

- f = 10MHz

Output

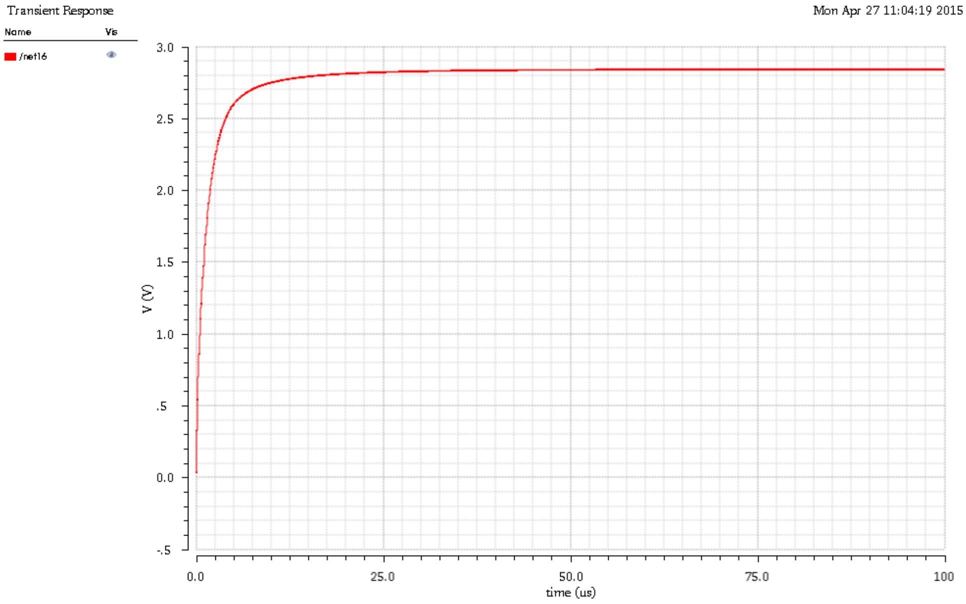


Figure I-26

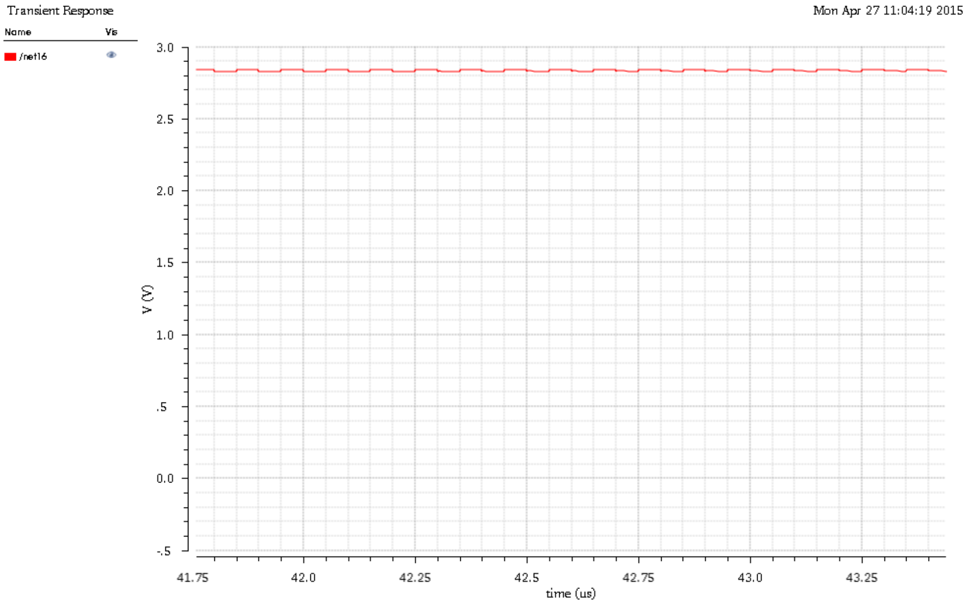


Figure I-27

- f = 100 MHz

Output

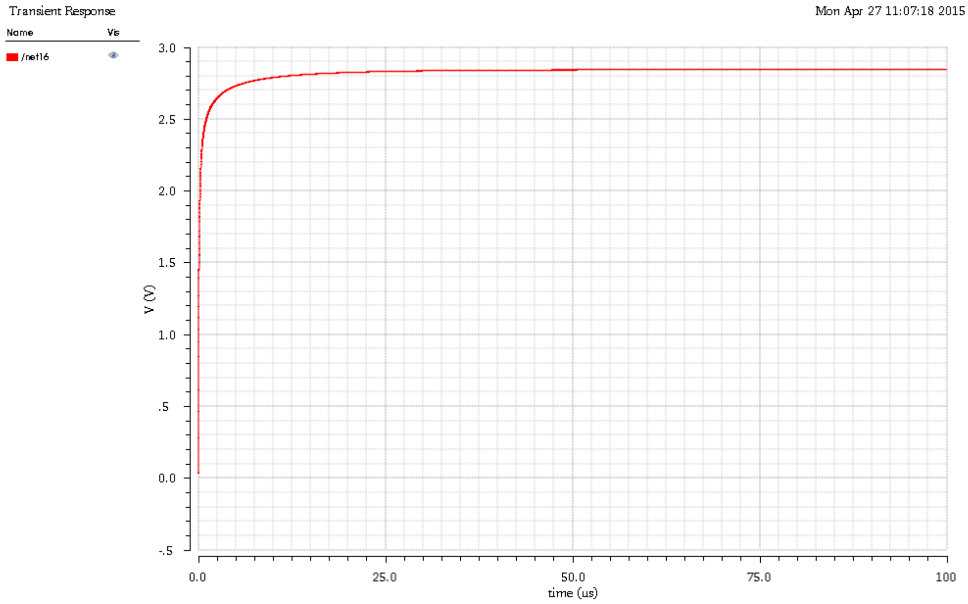


Figure I-28

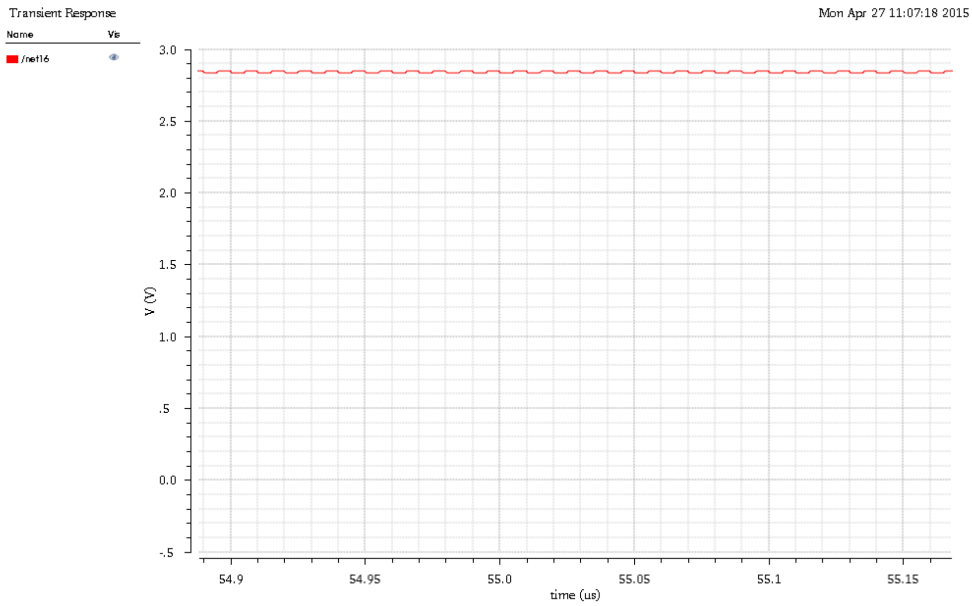


Figure I-29

2. Cross-coupled charge pump

- f=400 kHz

Output

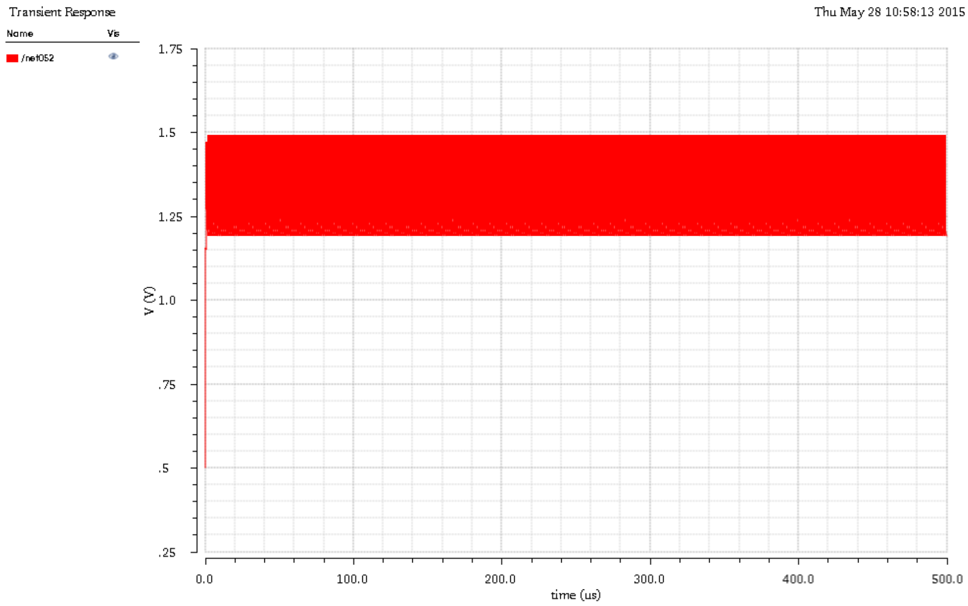


Figure I-30

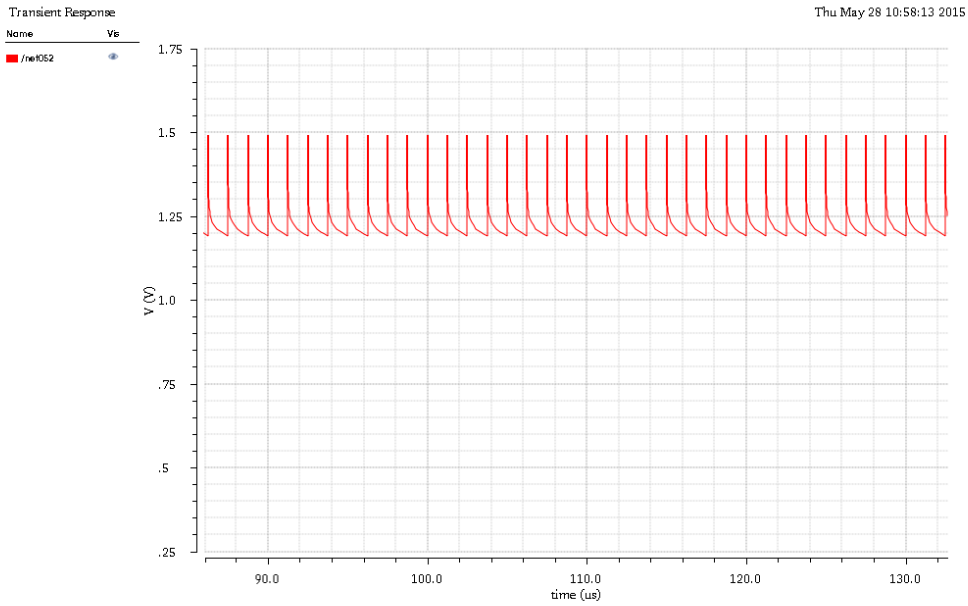


Figure I-31

- f=10MHz

Output

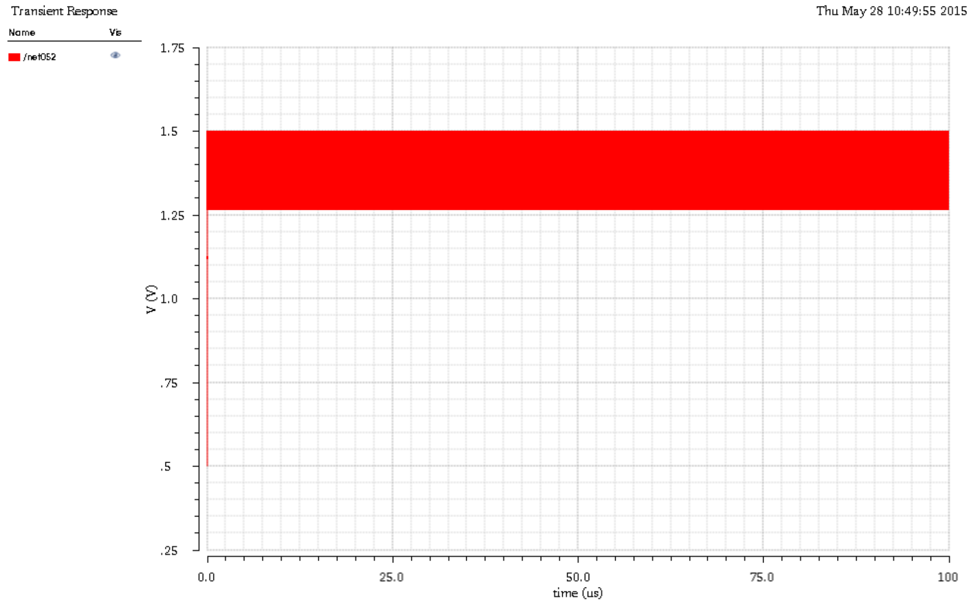


Figure I-32

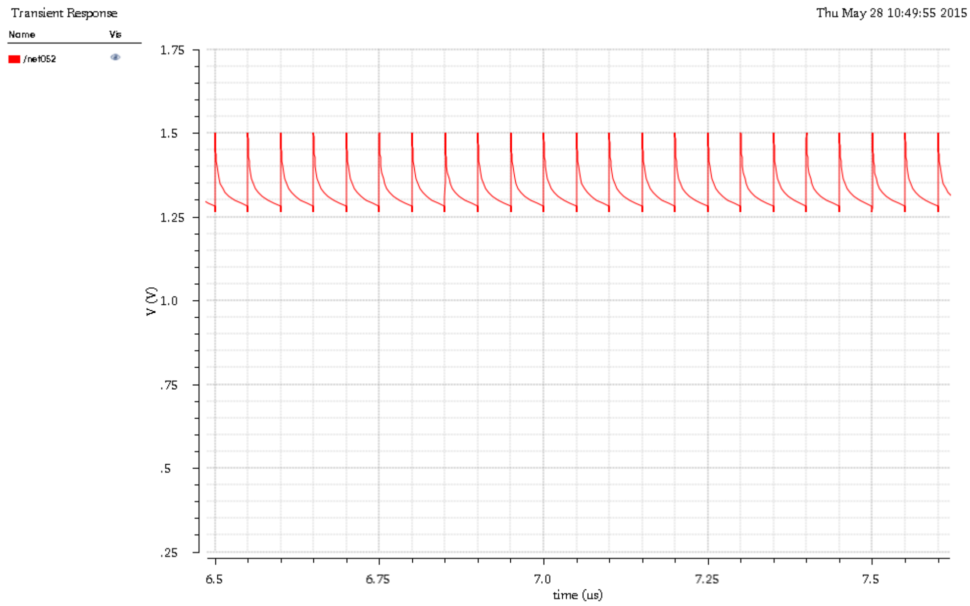


Figure I-33

- f=100MHz

Output

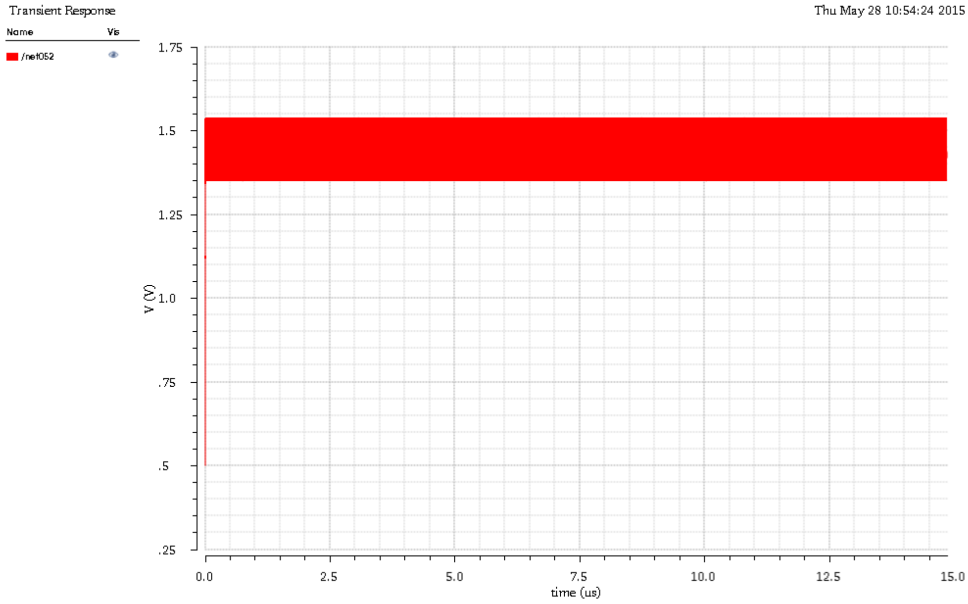


Figure I-34

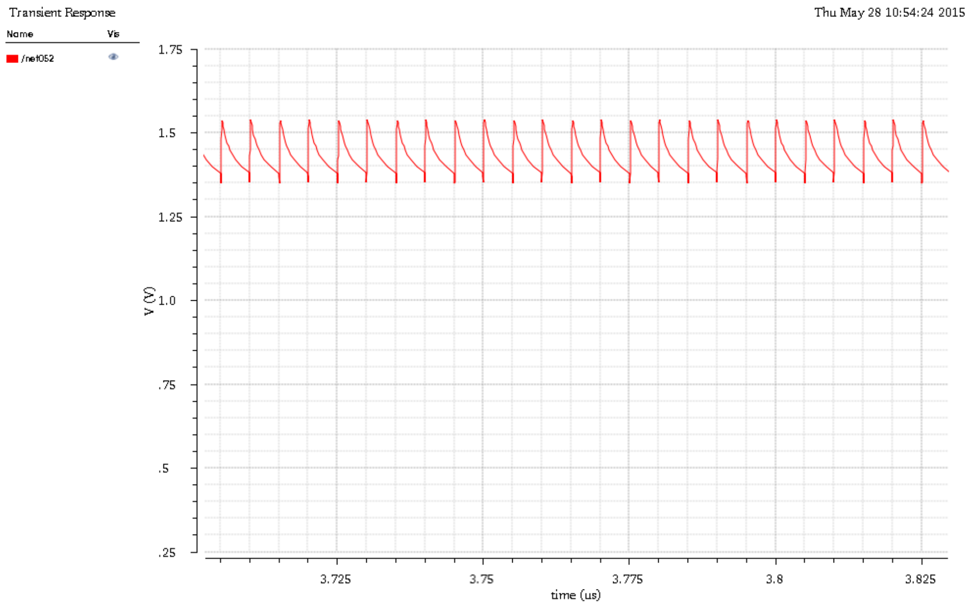


Figure I-35

C. Complete circuit

1. Ring oscillator + Dickson charge pump

- f=400 kHz

Output voltage and intensity

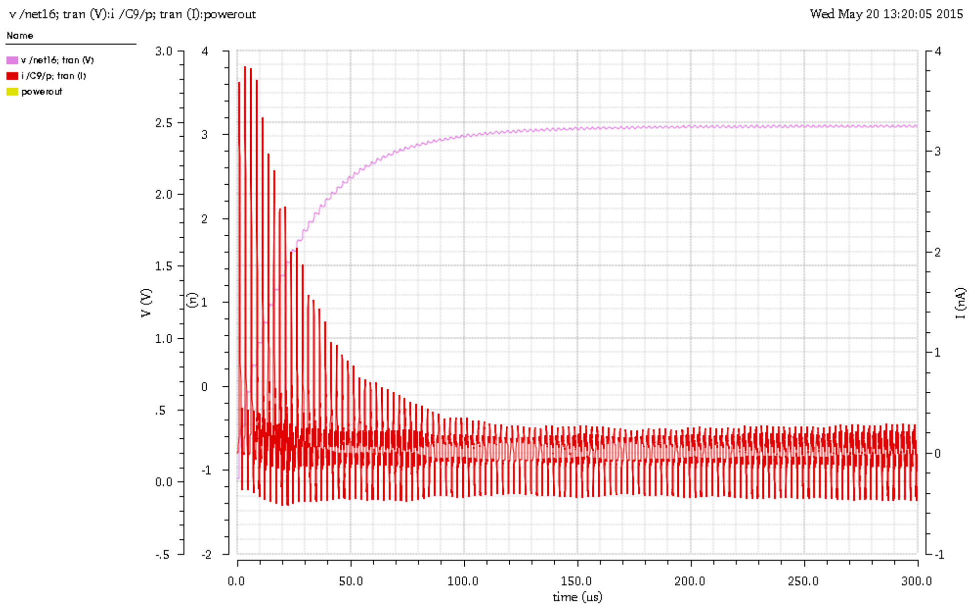


Figure I-36

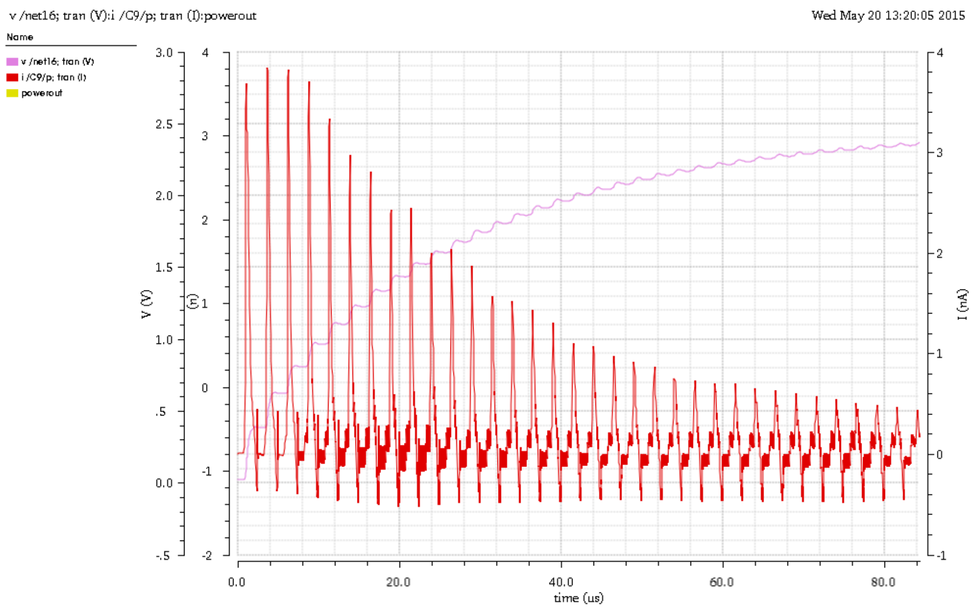


Figure I-37

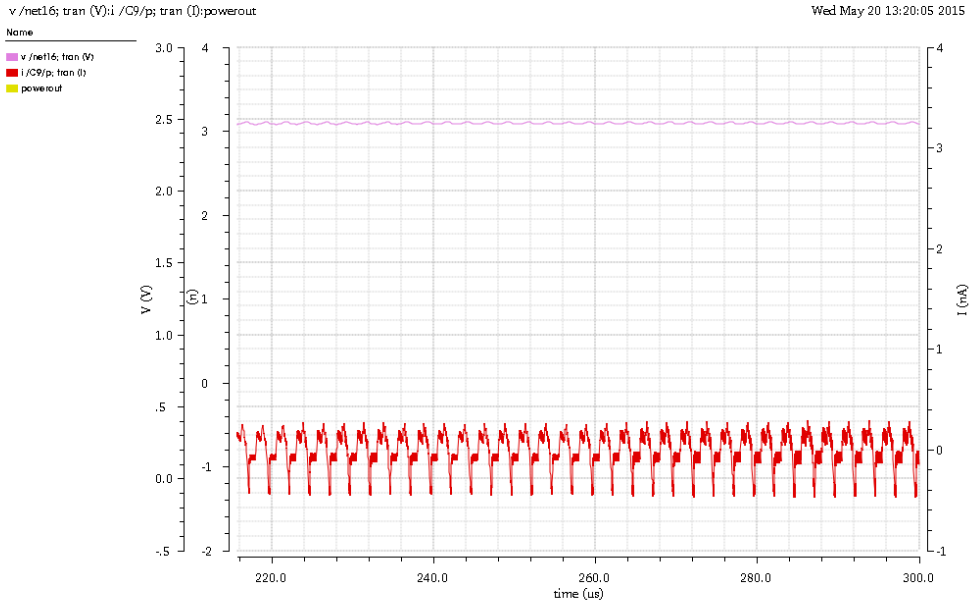


Figure I-38

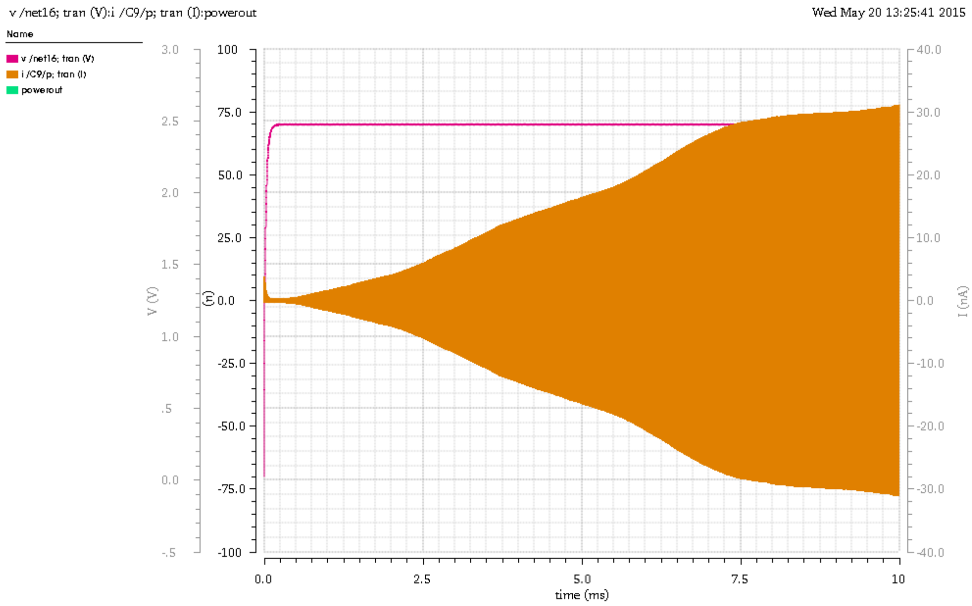


Figure I-39

Powerout

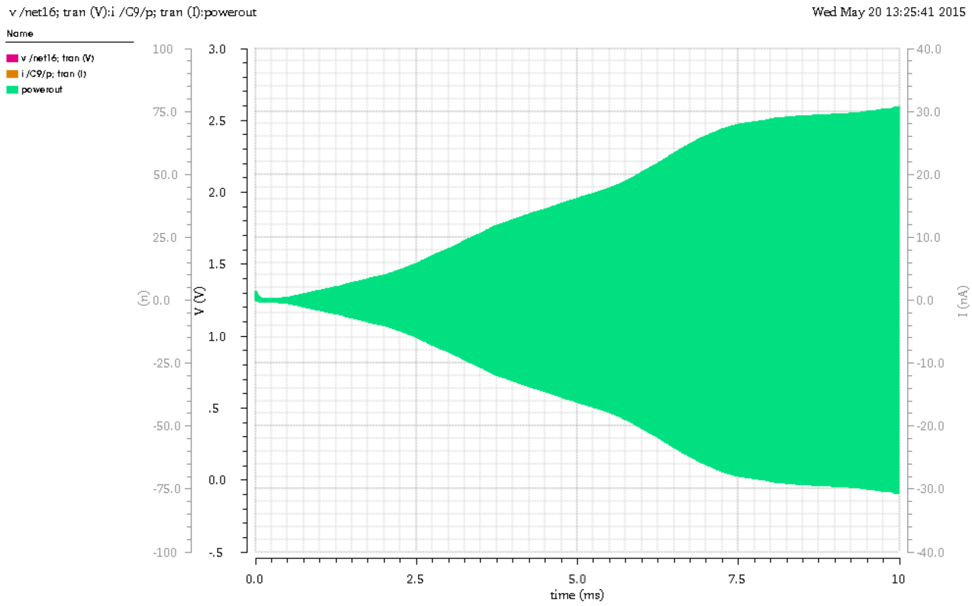


Figure I-40

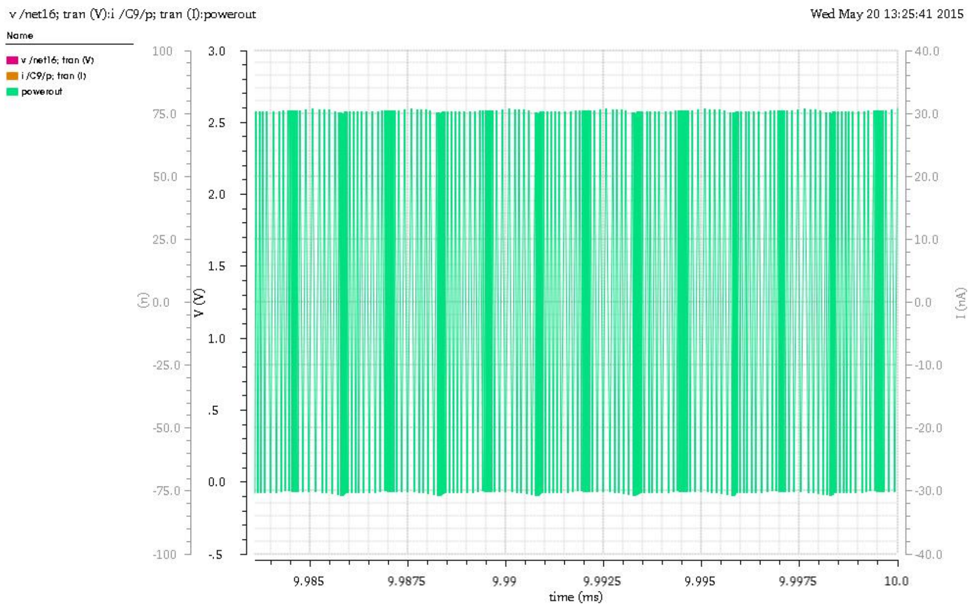


Figure I-41

- f=10MHz

Output voltage and intensity

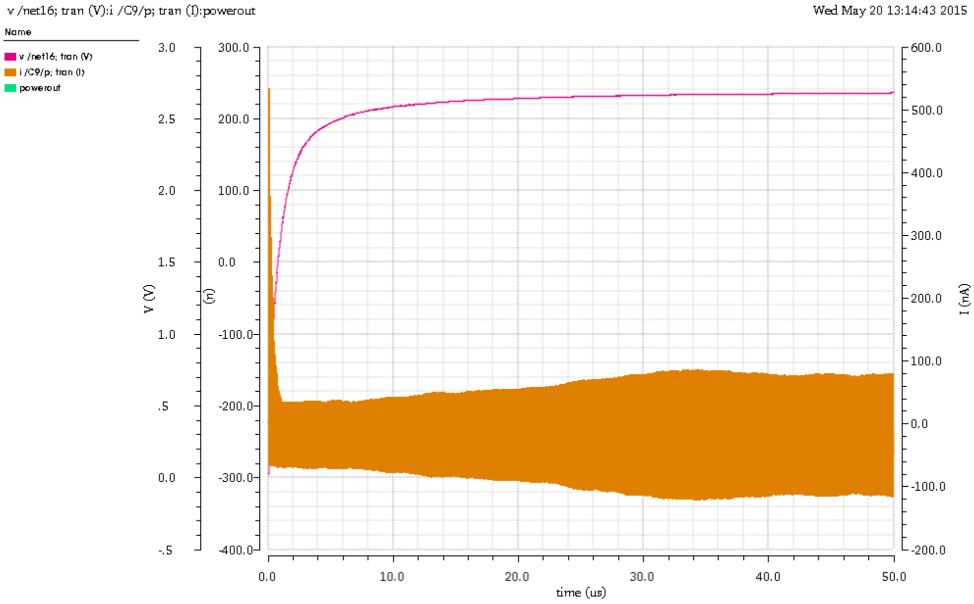


Figure I-42

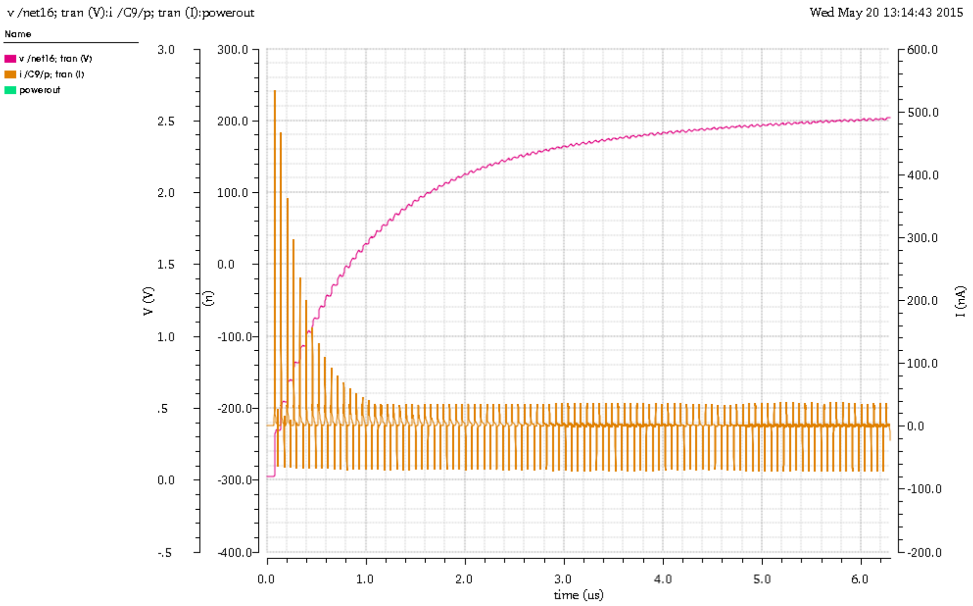


Figure I-43

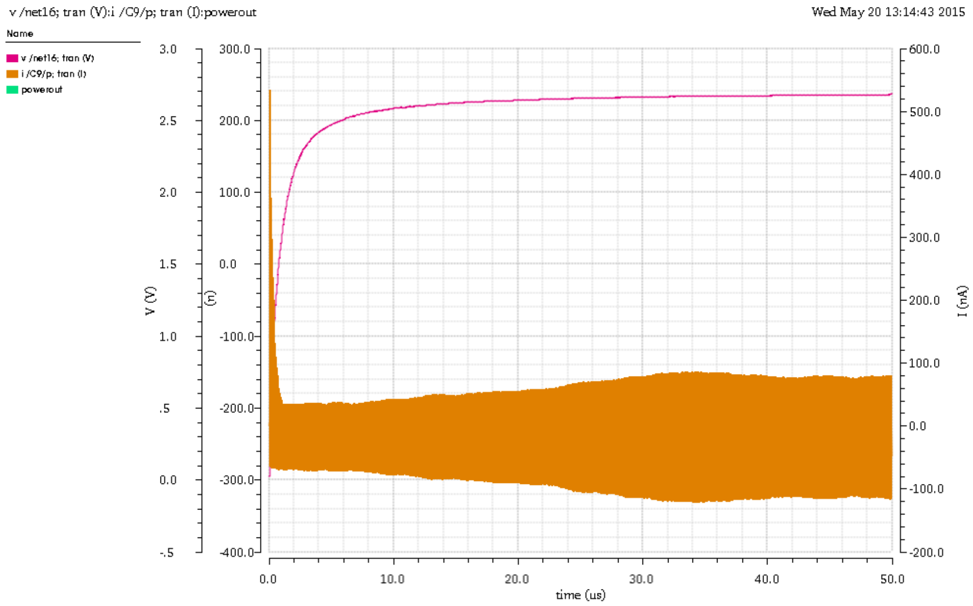


Figure I-44

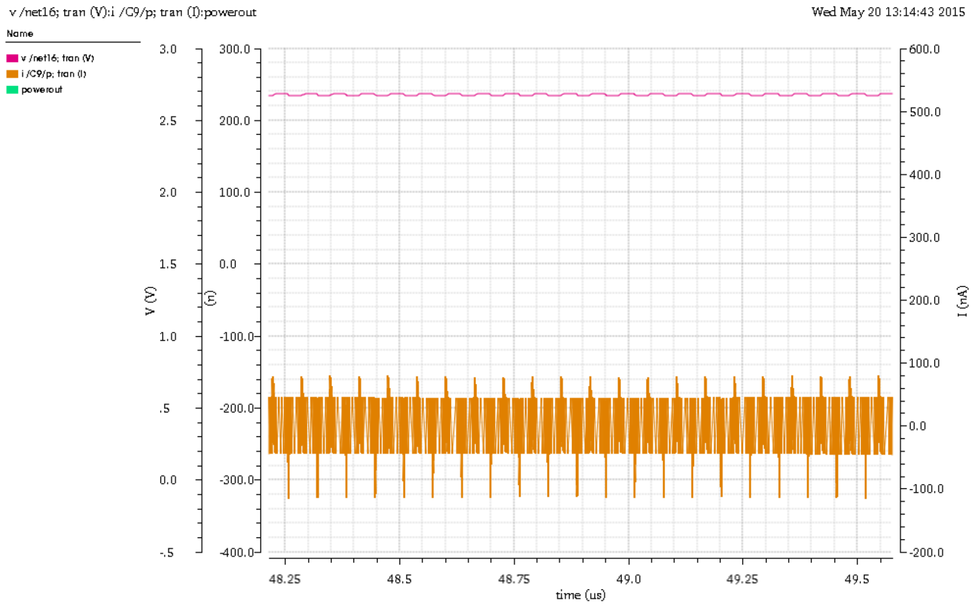


Figure I-45

Output power

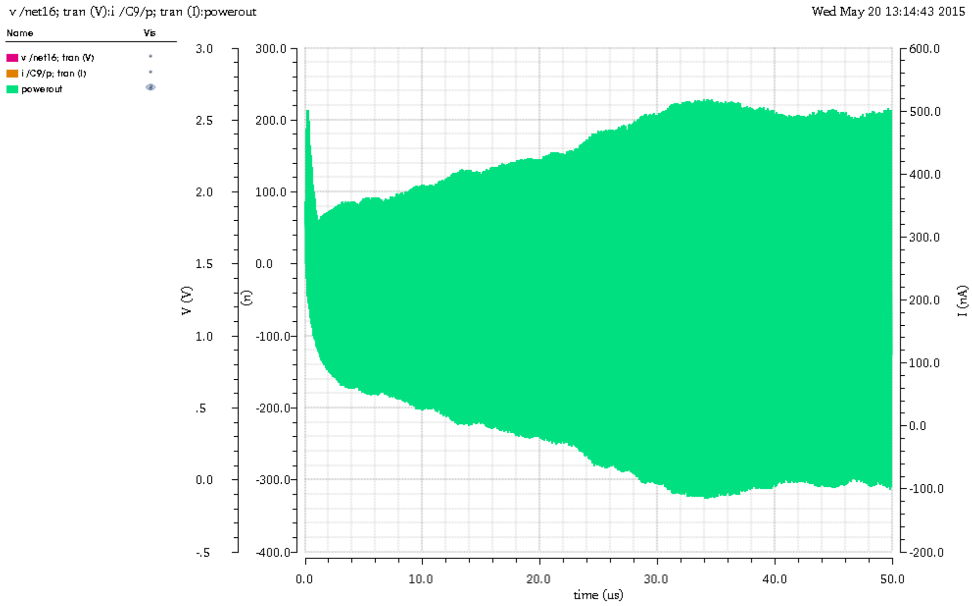


Figure I-46

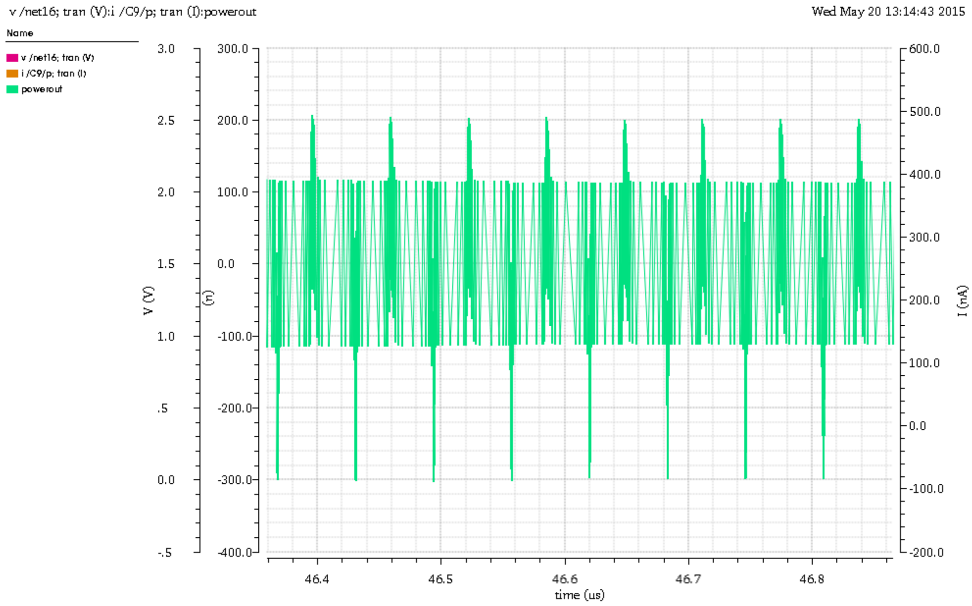


Figure I-47

- f=110MHz

Output voltage and intensity

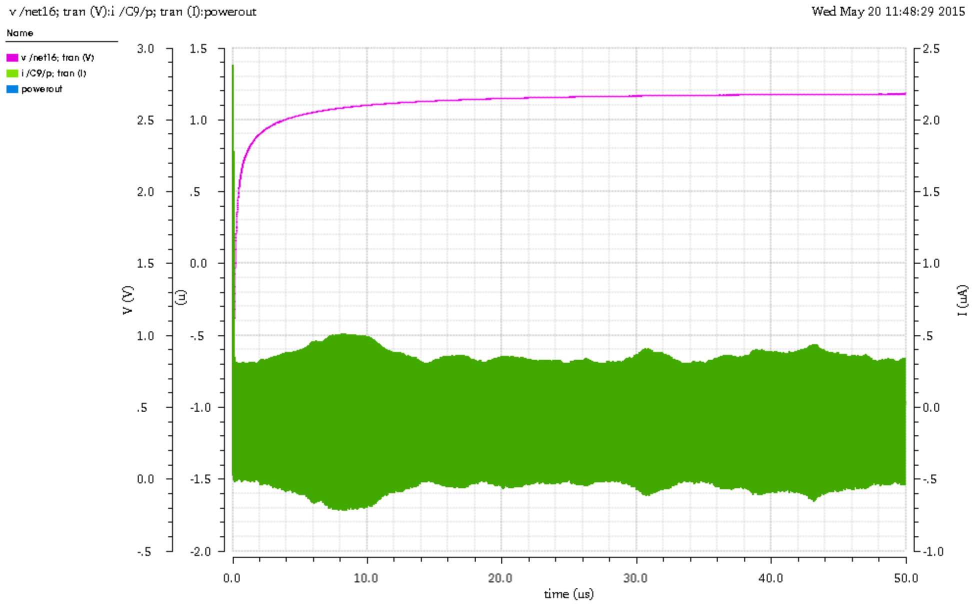


Figure I-48

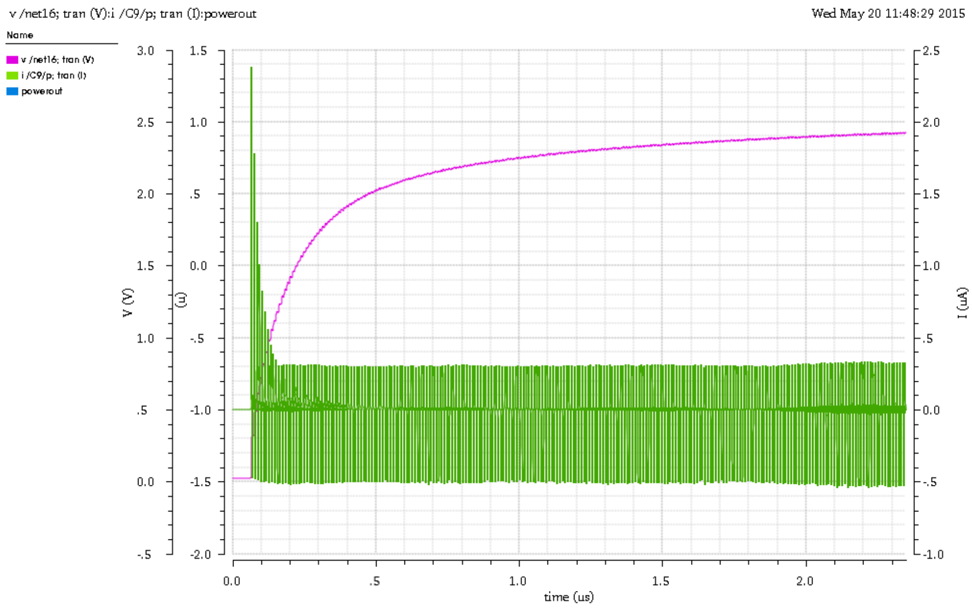


Figure I-49

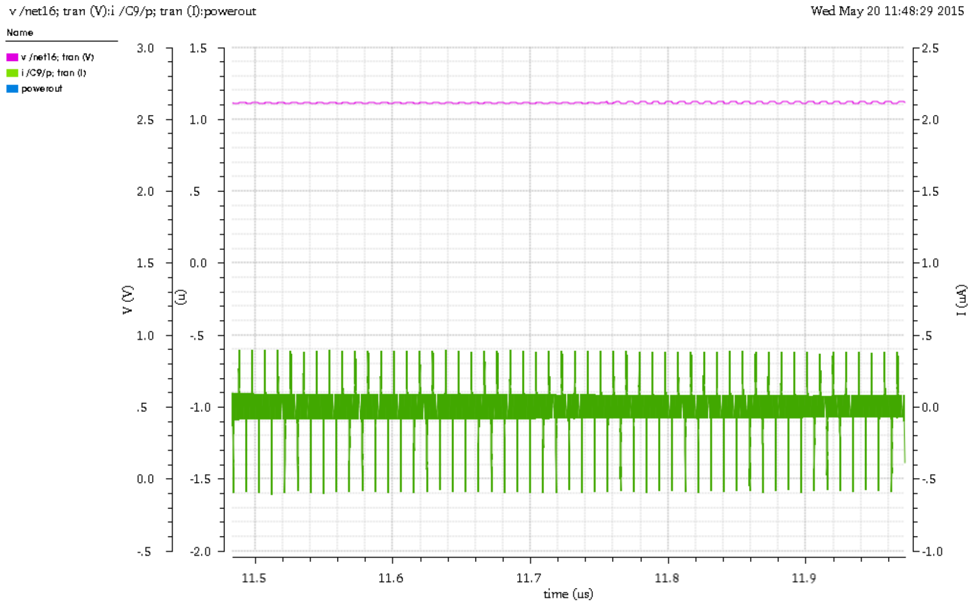


Figure I-50

Output power

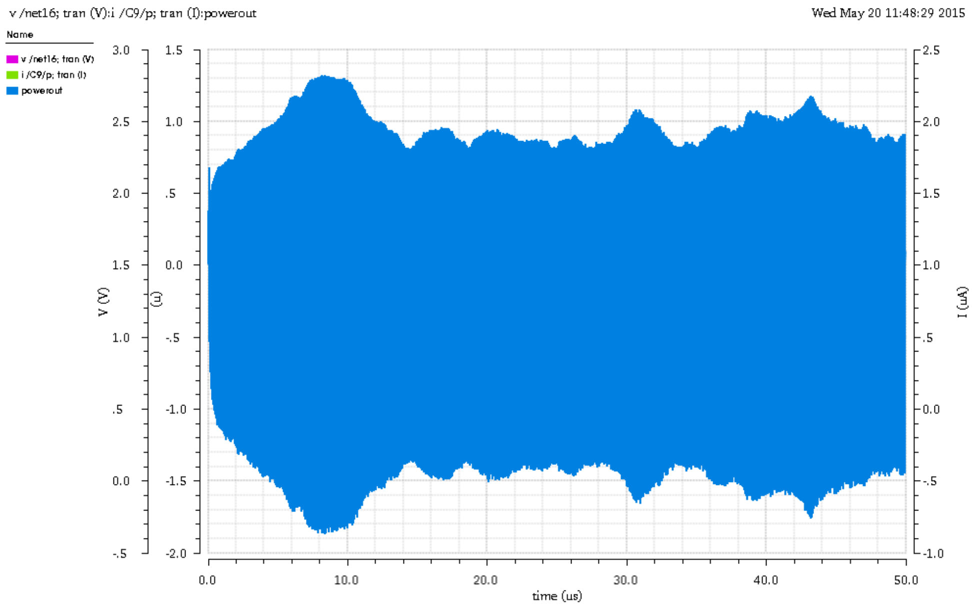


Figure I-51

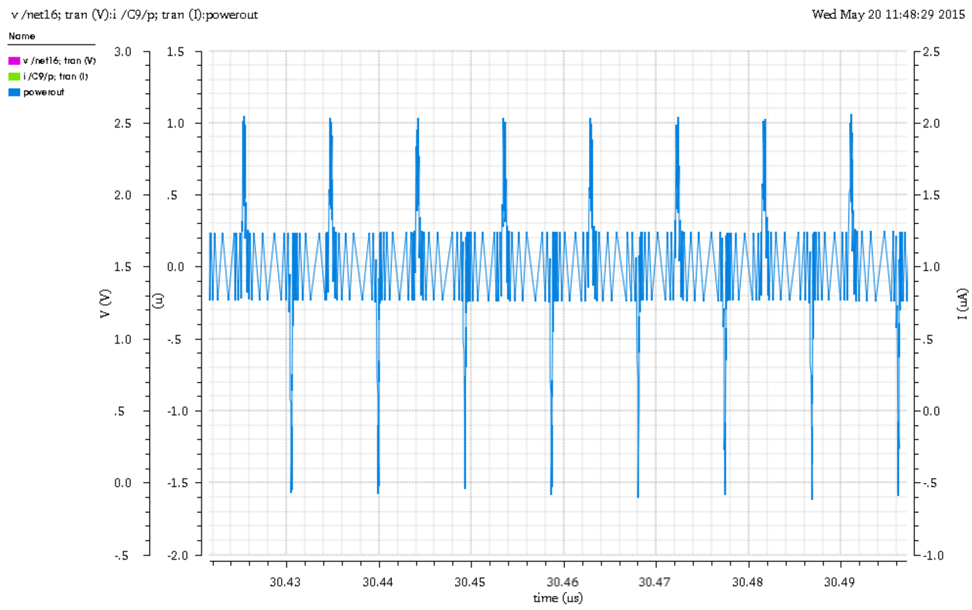


Figure I-52

2. Astable oscillator + Dickon charge pump

Frequency [kHz]	R1 [kΩ]	R2 [kΩ]	R3 [kΩ]	R4 [kΩ]	C [pF]	Cp [fF]	Transistor number of fingers
$10 \cdot 10^3$	2,1	120	120	2	2	1	5

Table I-1

- f=400 kHz

Output voltage and intensity

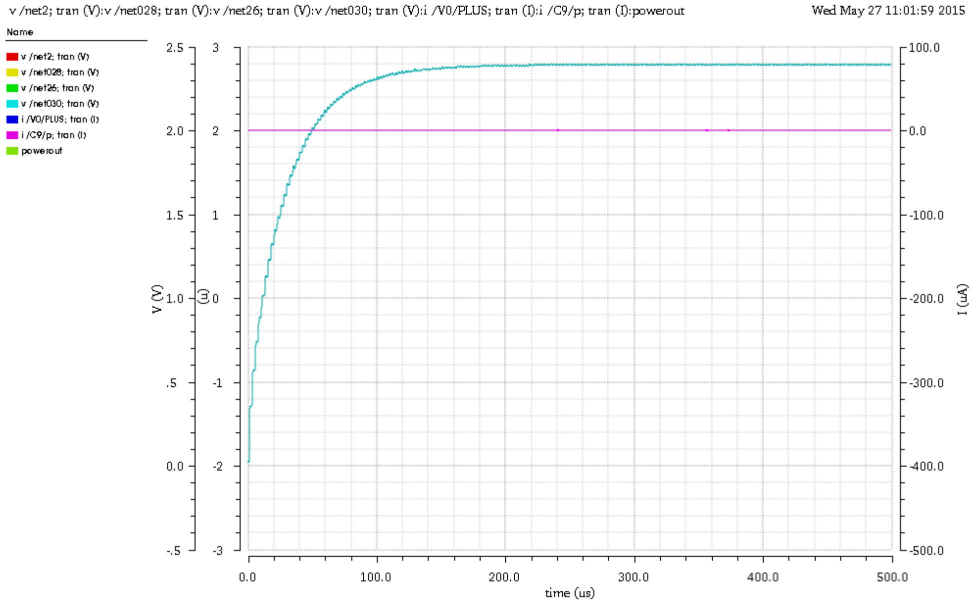


Figure I-53

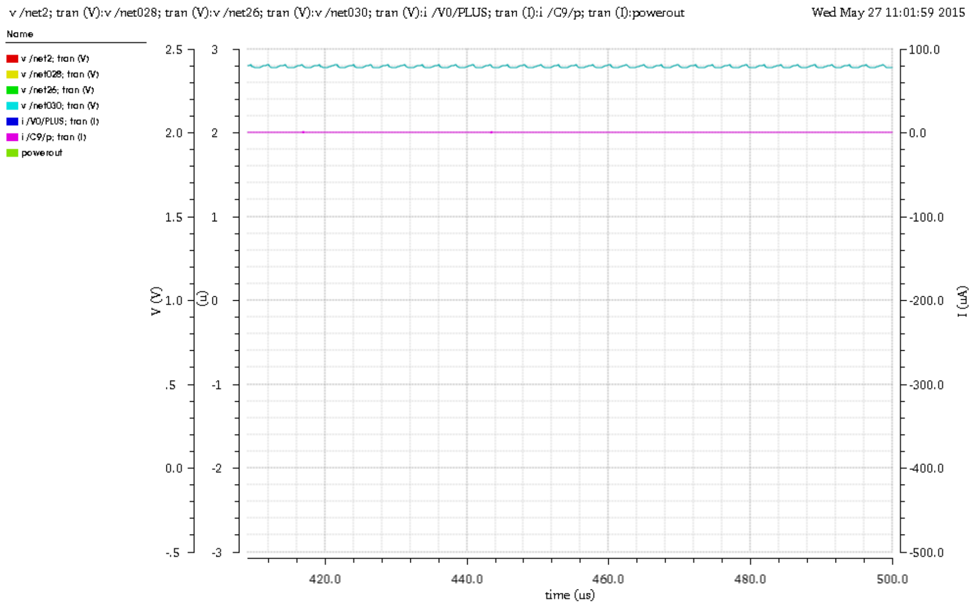


Figure I-54

Output power

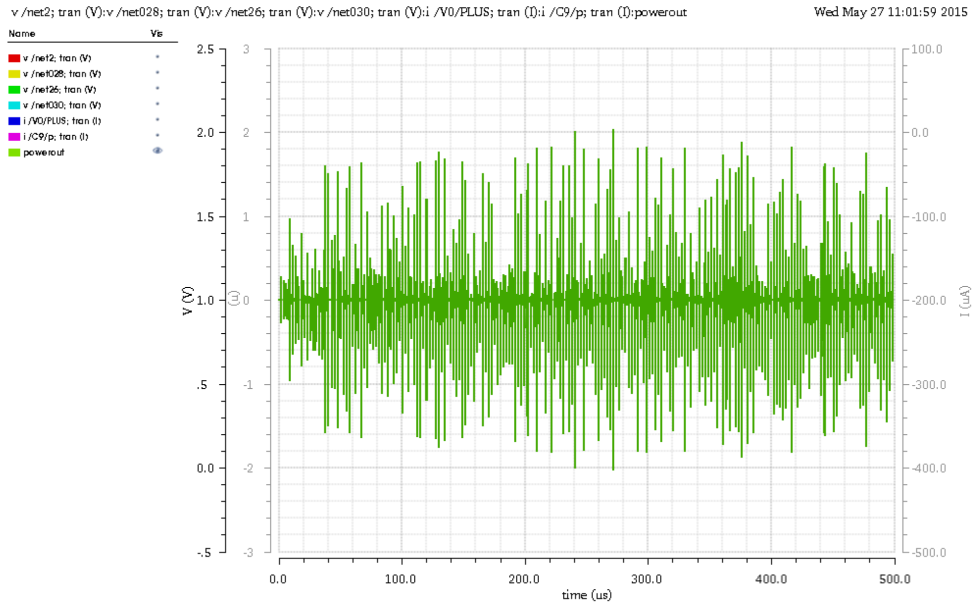


Figure I-55

- f= 10MHz

Oscillations

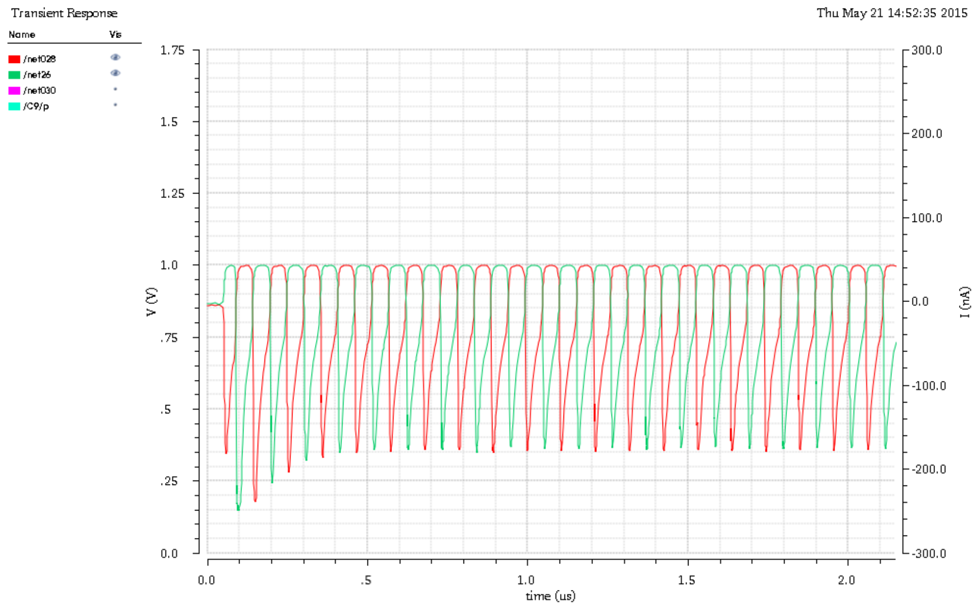


Figure I-56

Output voltage and intensity

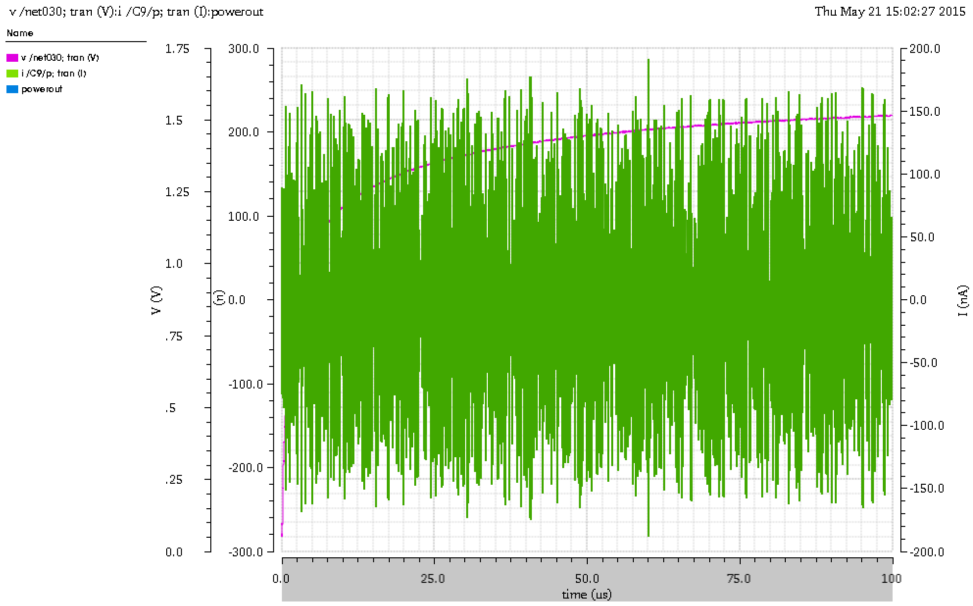


Figure I-57

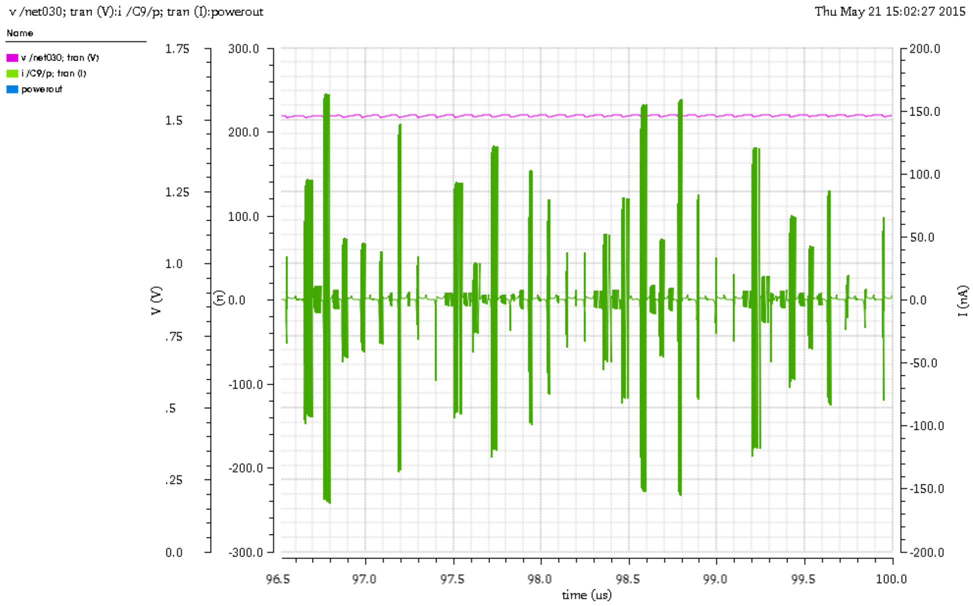


Figure I-58

Output power

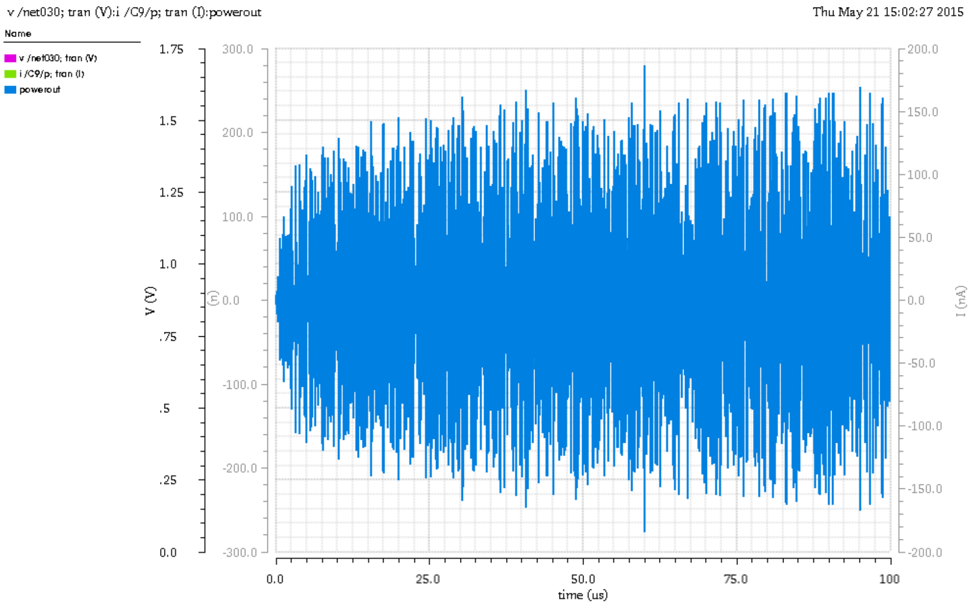


Figure I-59

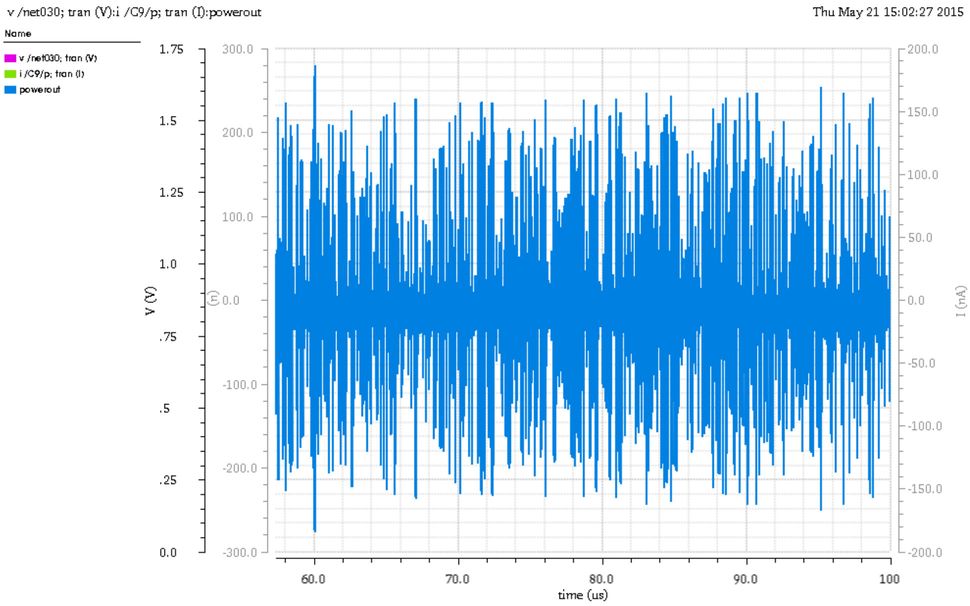


Figure I-60

- f= 50MHz

Oscillations

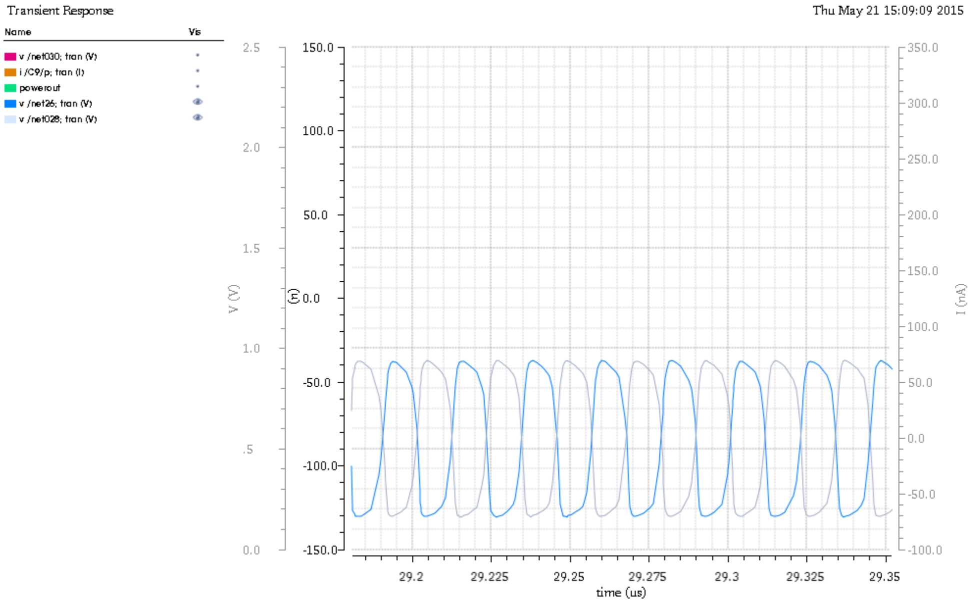


Figure I-61

Output voltage and intensity

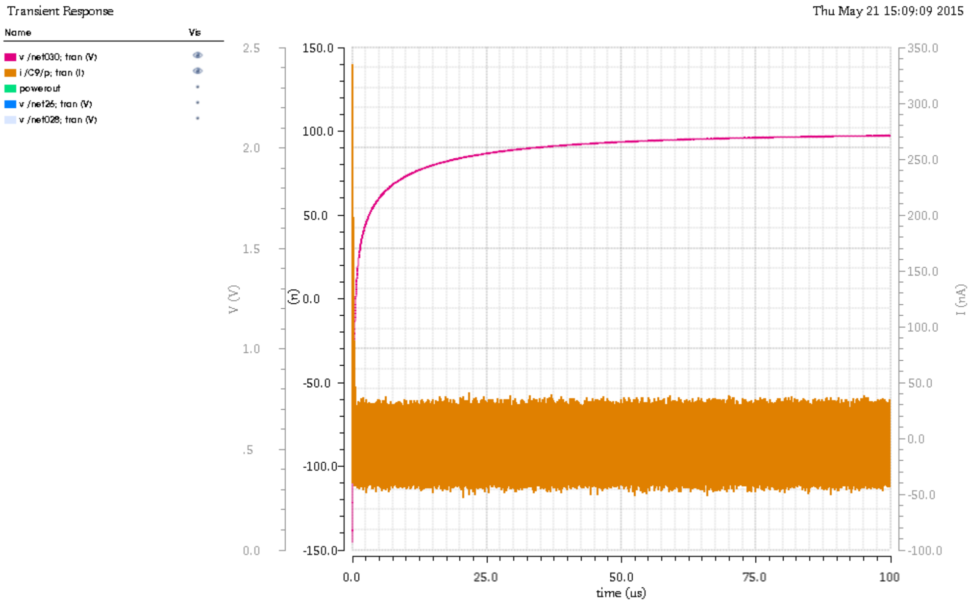


Figure I-62

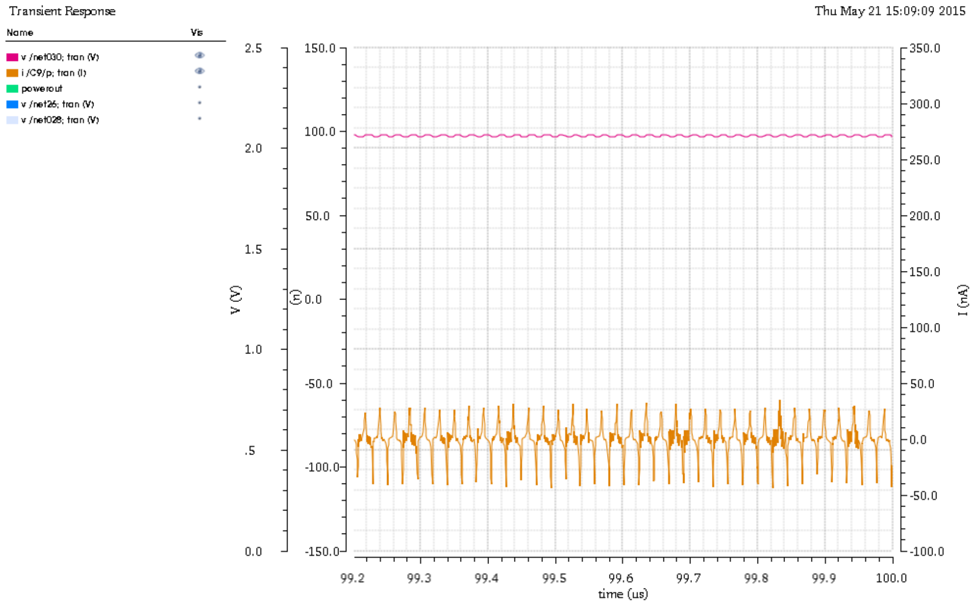


Figure I-63

Output power

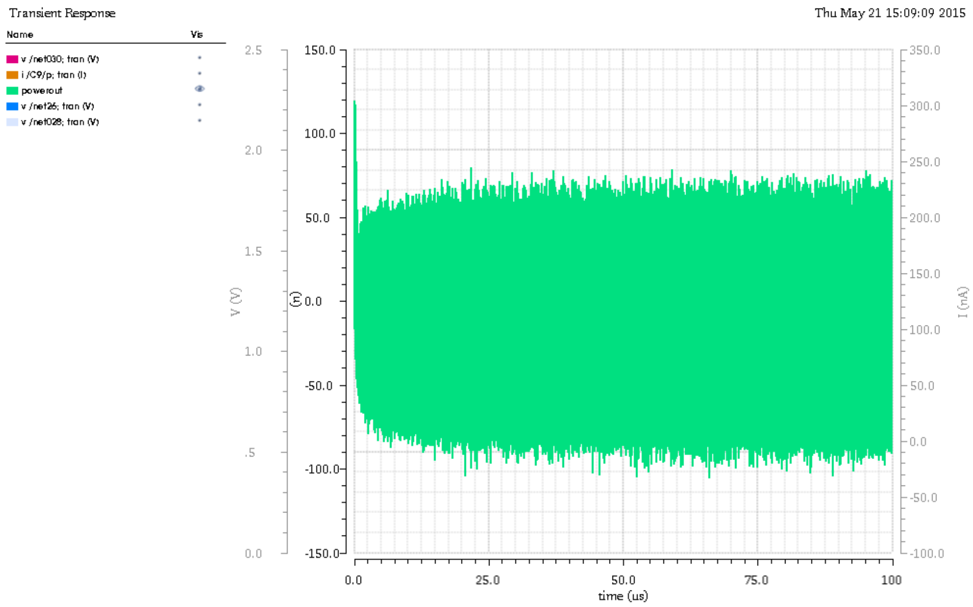


Figure I-64

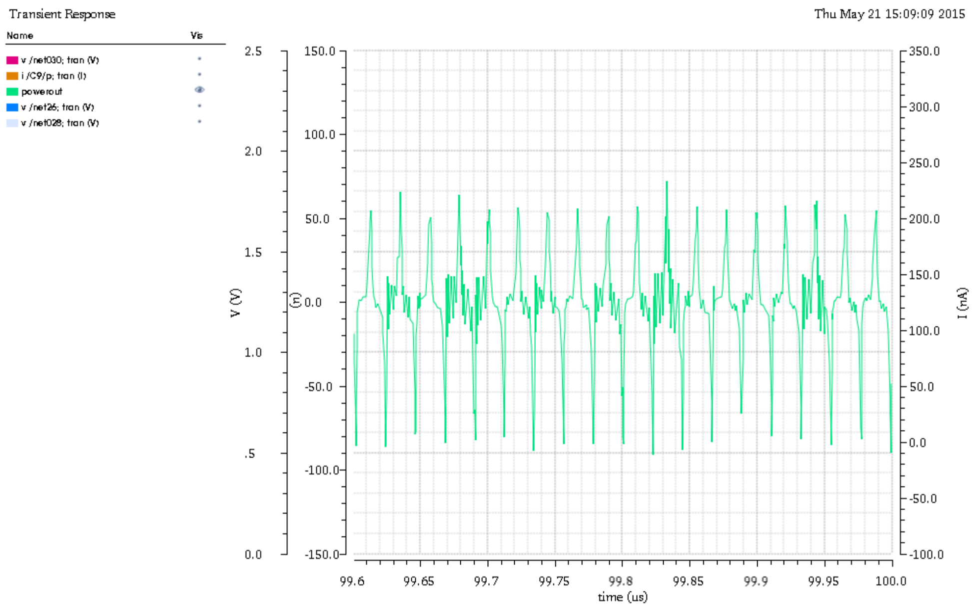


Figure I-65

3. Ring oscillator + Cross-coupled charge pump

- f=400 kHz

Output voltage and intensity

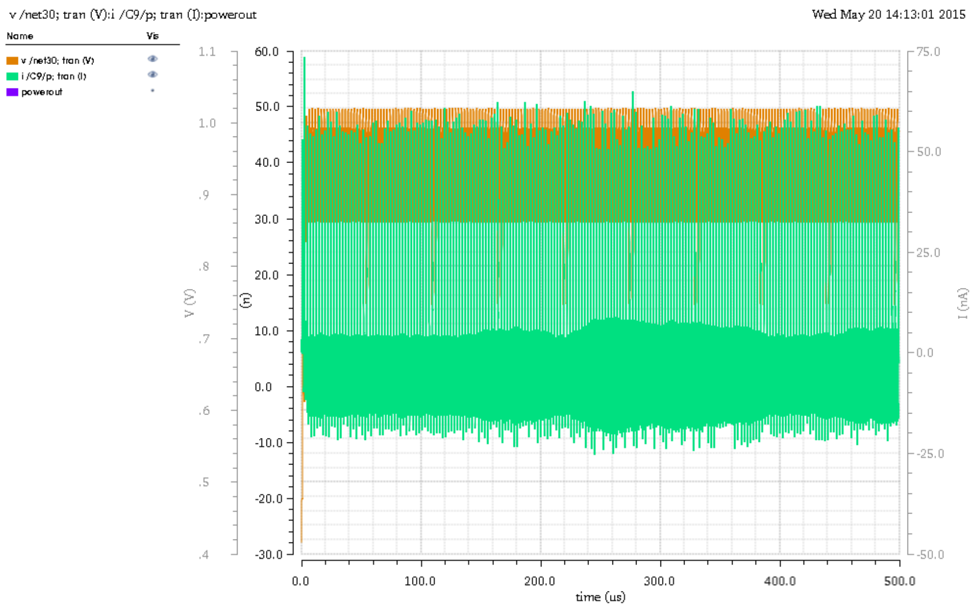


Figure I-66

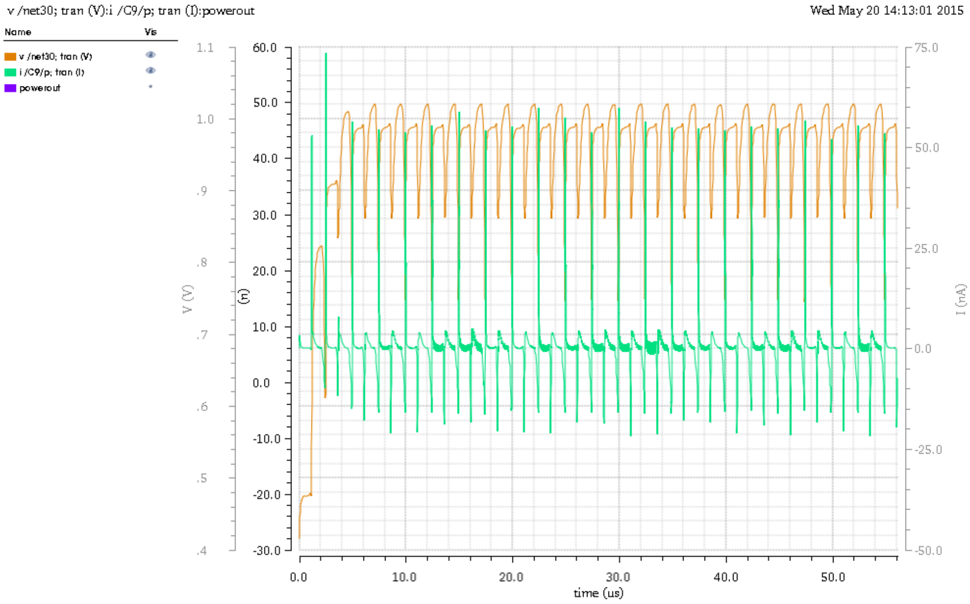


Figure I-67

Output power

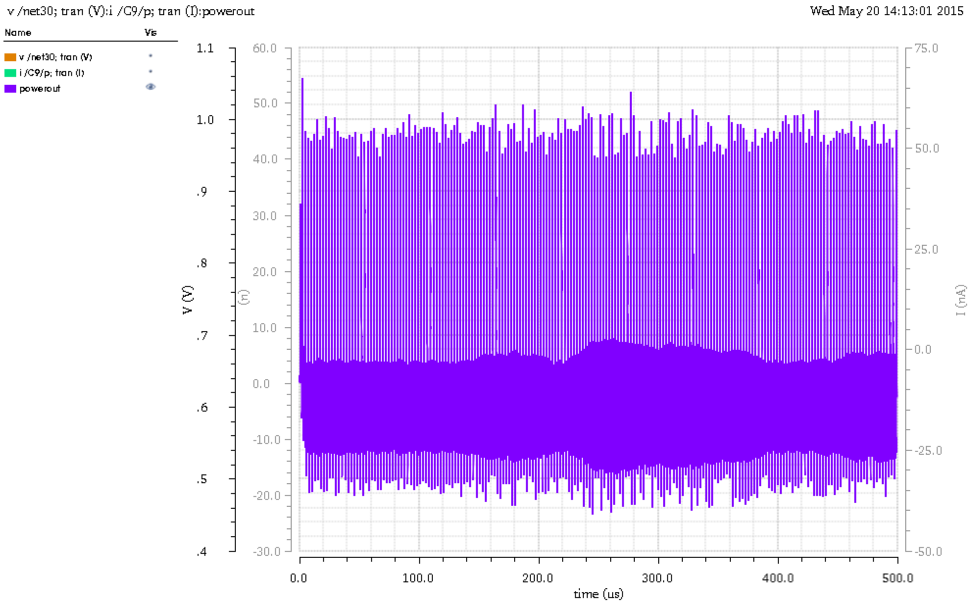


Figure I-68

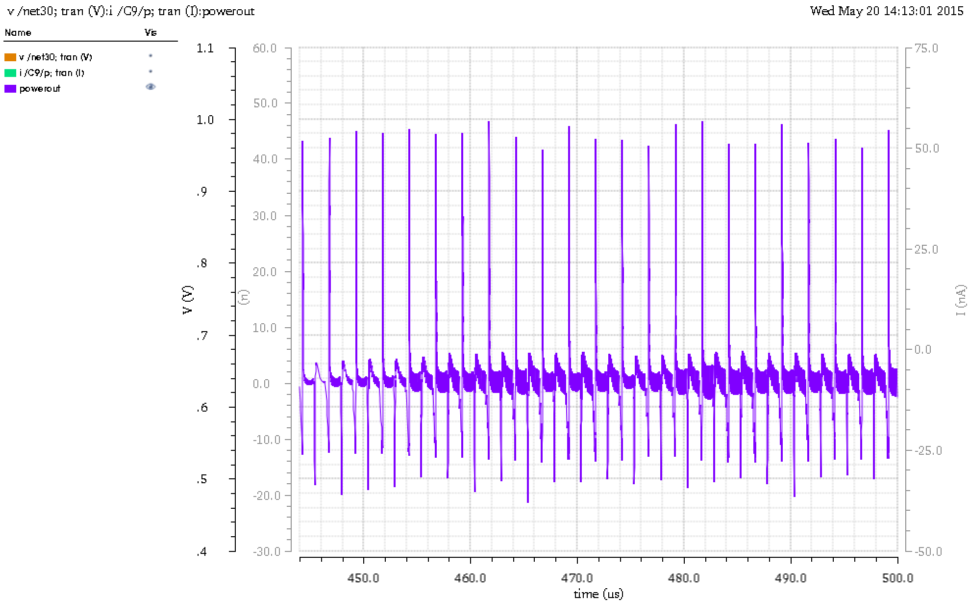


Figure I-69

- f= 10MHz

Output voltage and intensity

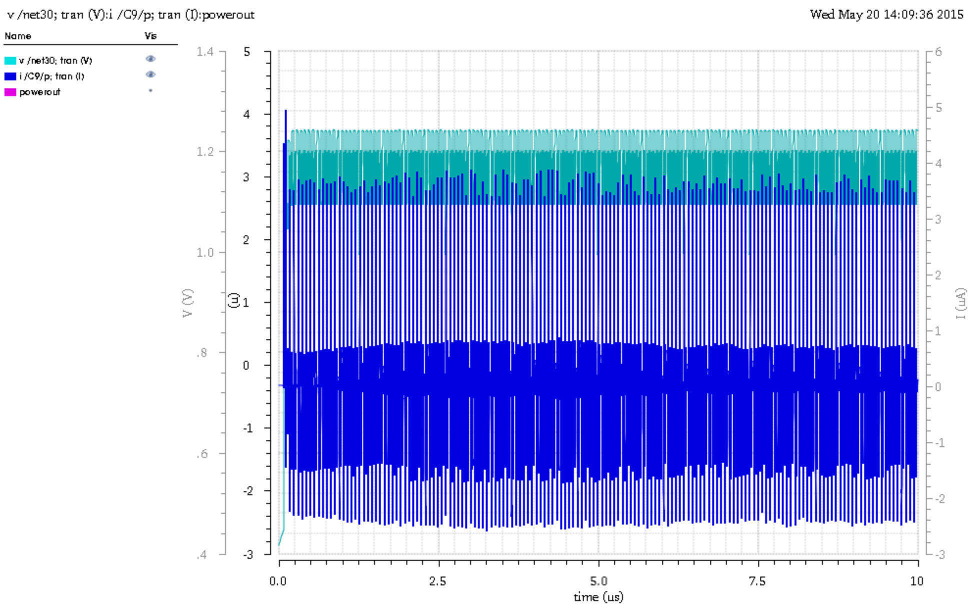


Figure I-70

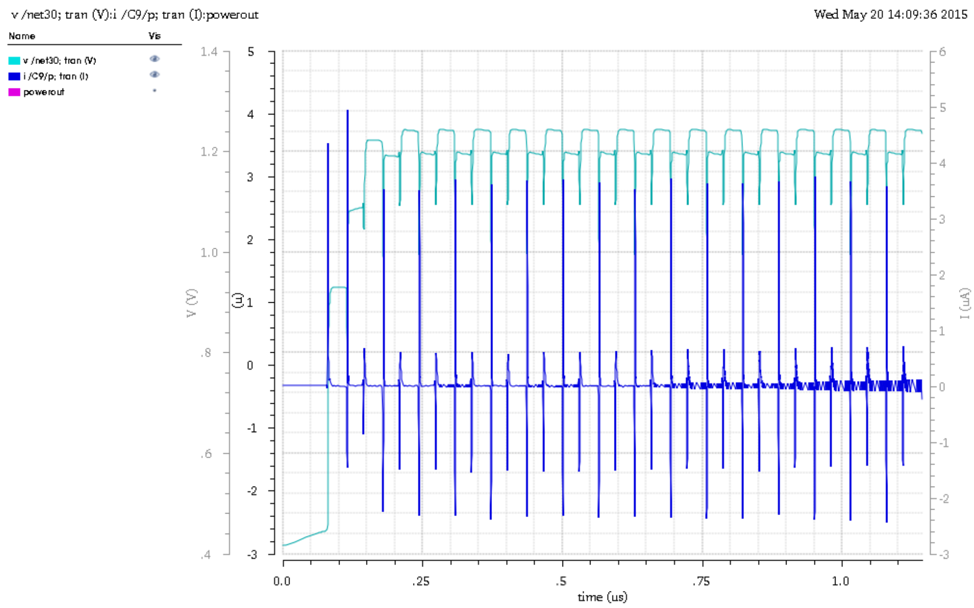


Figure I-71

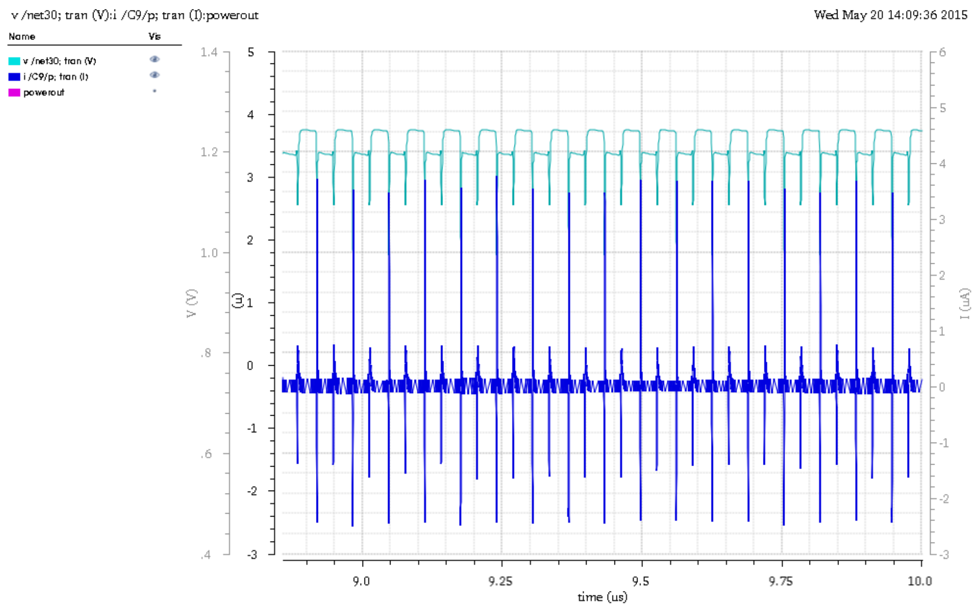


Figure I-72

Output power

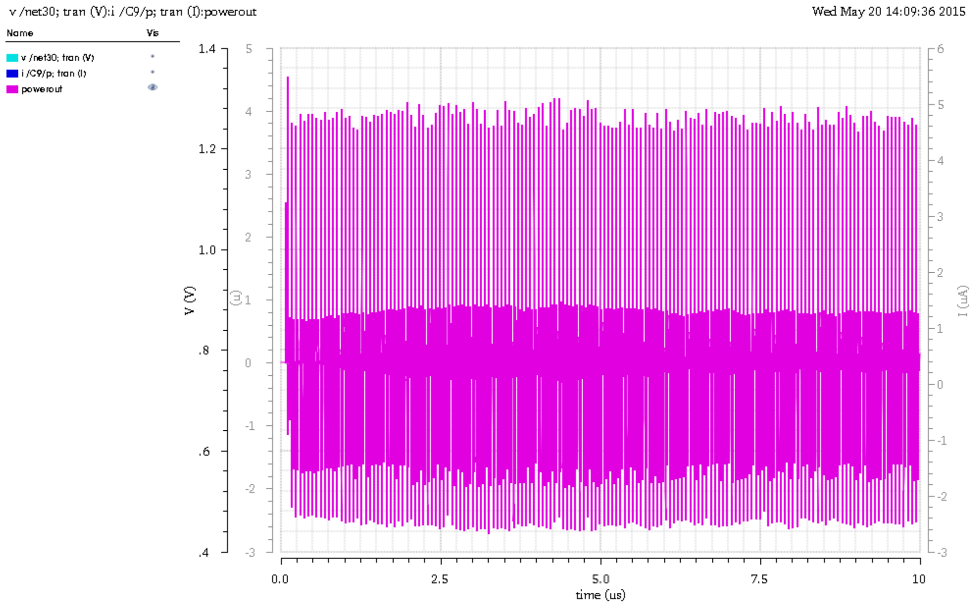


Figure I-73

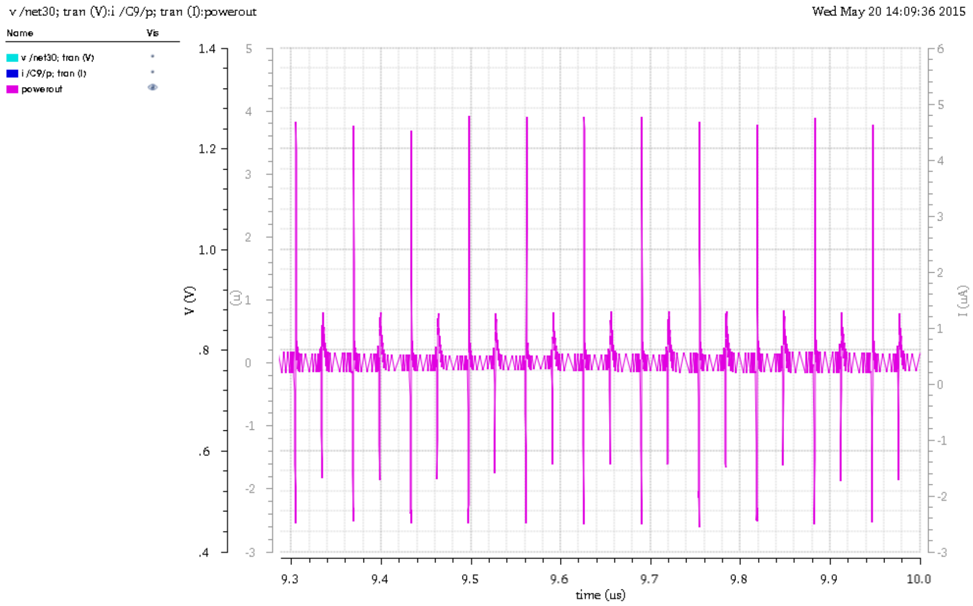


Figure I-74

- f=100MHz

Output voltage and intensity

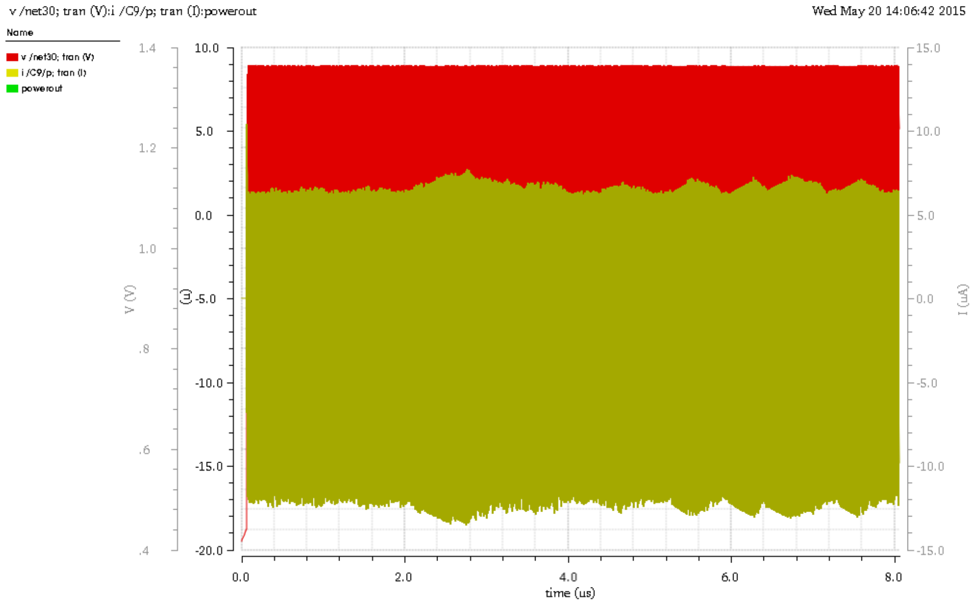


Figure I-75

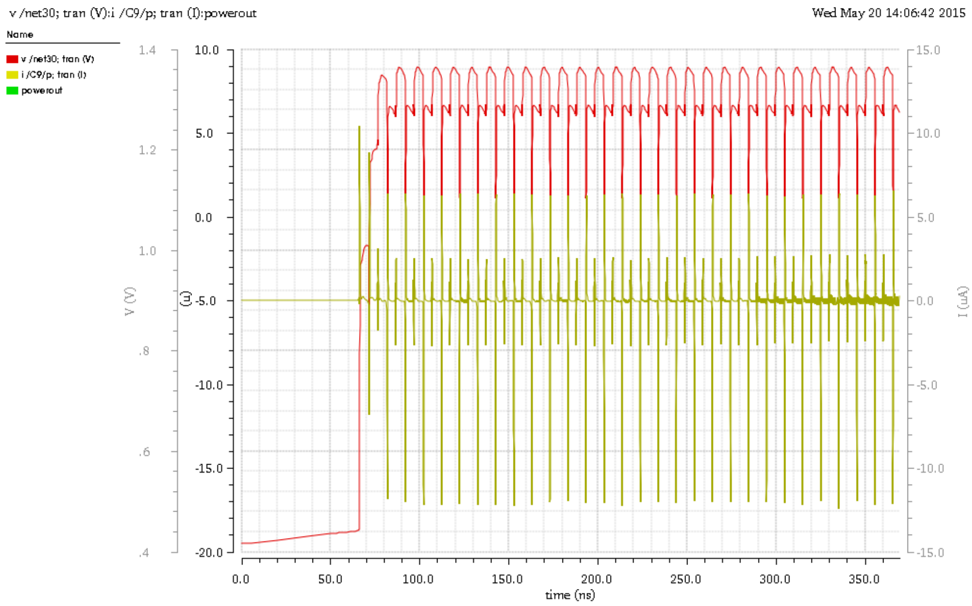


Figure I-76

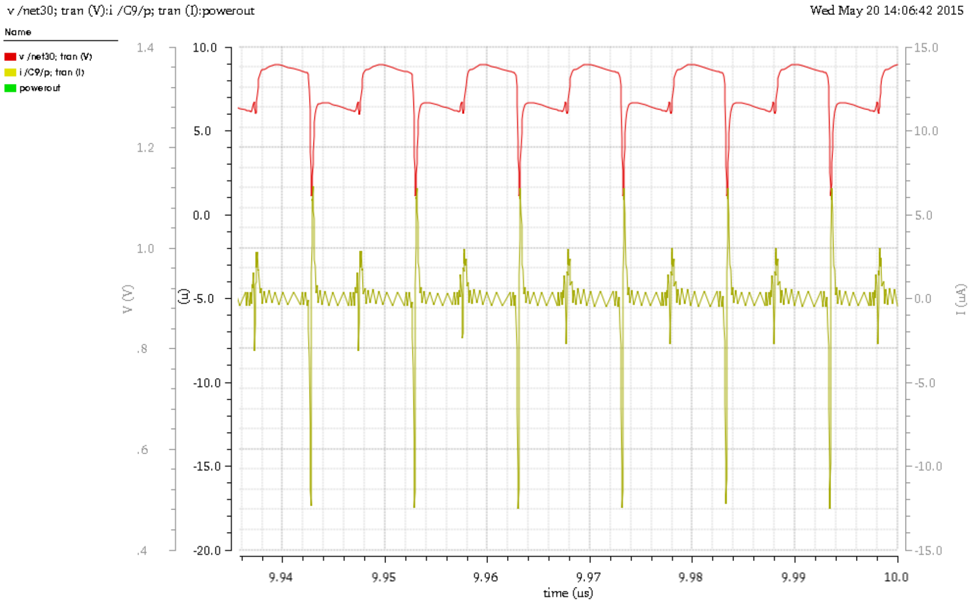


Figure I-77

Output power

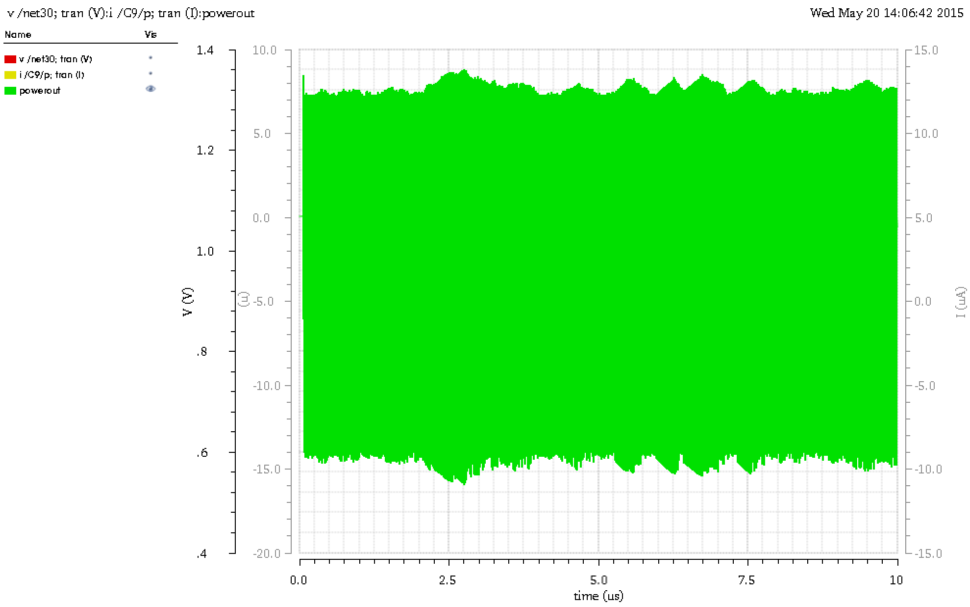


Figure I-78

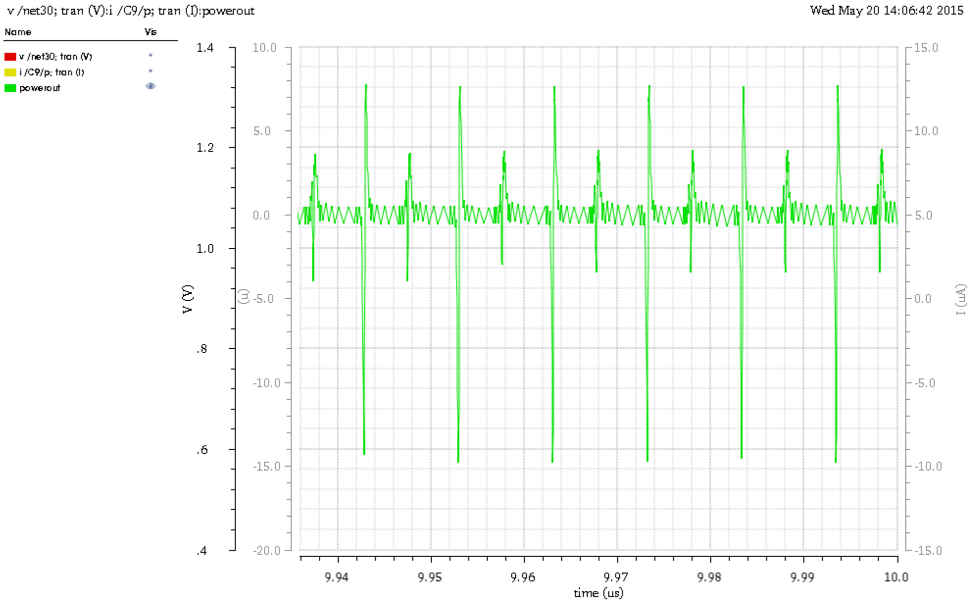


Figure I-79

4. Astable oscillator + Cross-coupled charge pump

Frequency [kHz]	R1 [kΩ]	R2 [kΩ]	R3 [kΩ]	R4 [kΩ]	C [pF]	Cp [fF]	Transistor number of fingers
400	4	40	40	4,01	130	1	1
$10 \cdot 10^3$	1,5	140	140	1,6	3	1	5
$100 \cdot 10^3$	1	20	20	1,01	4	10	10

Table I-2 Values when simulating the two circuits together

- f= 400 kHz

Oscillations

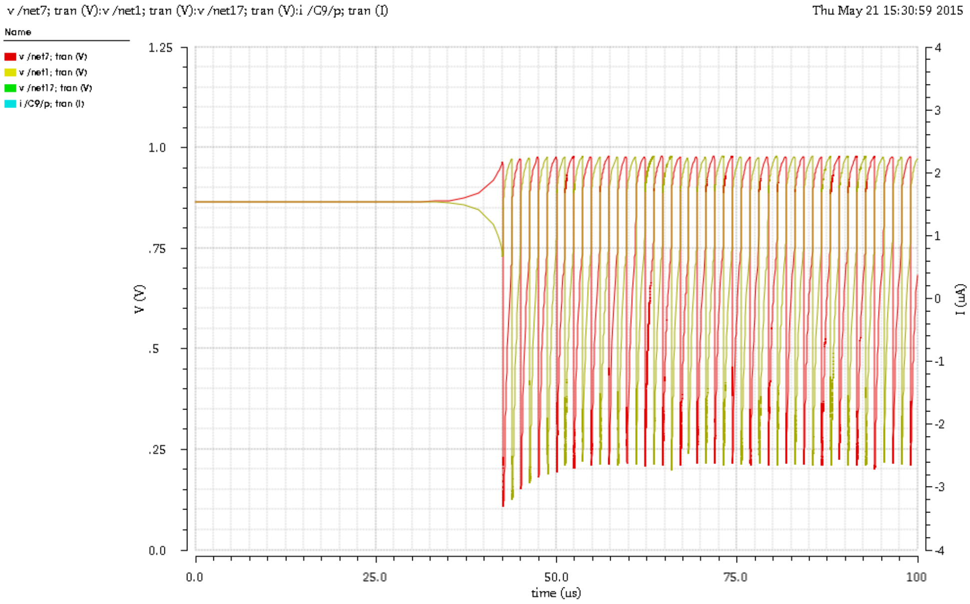


Figure I-80

Output voltage and intensity

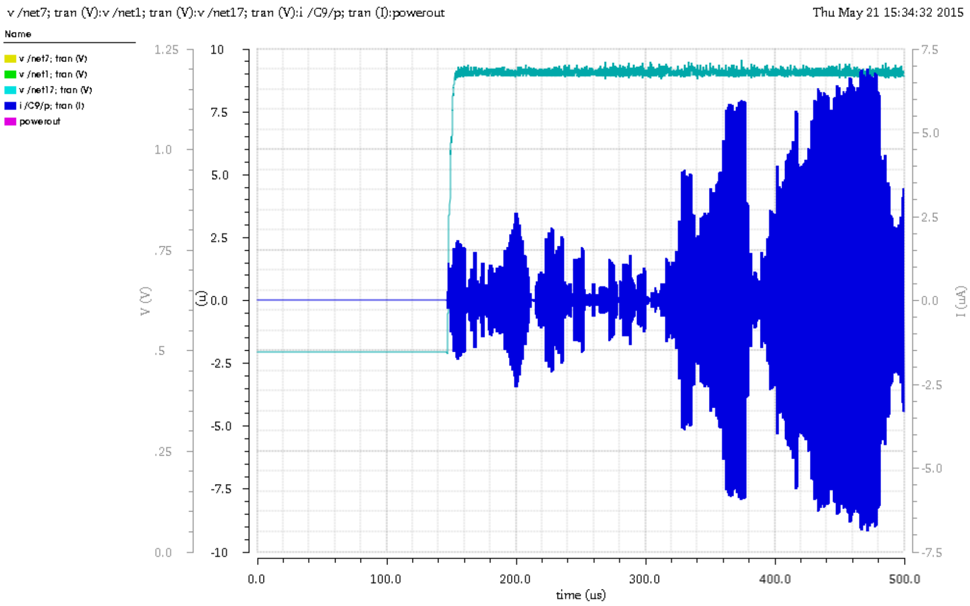


Figure I-81

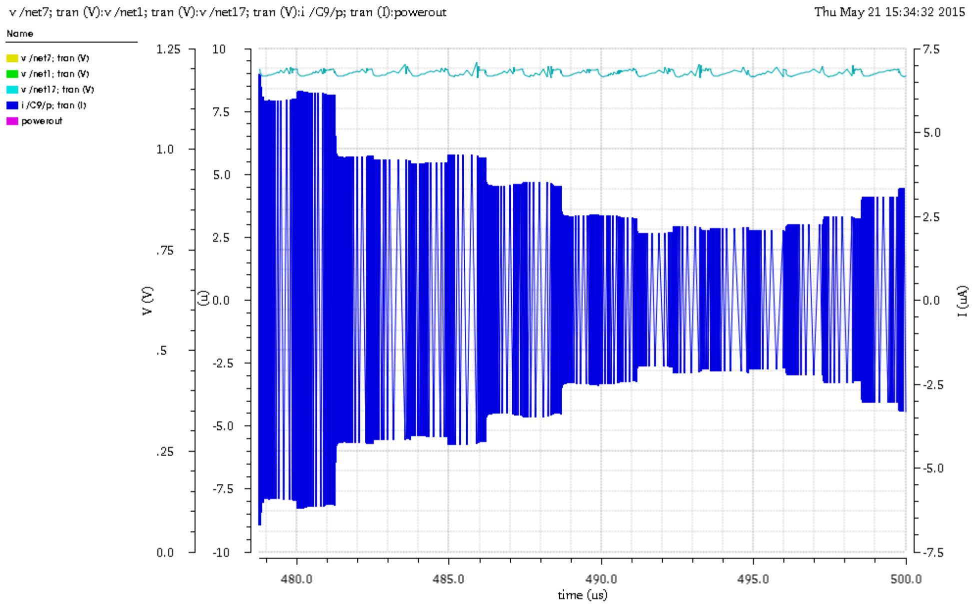


Figure I-82

Output power

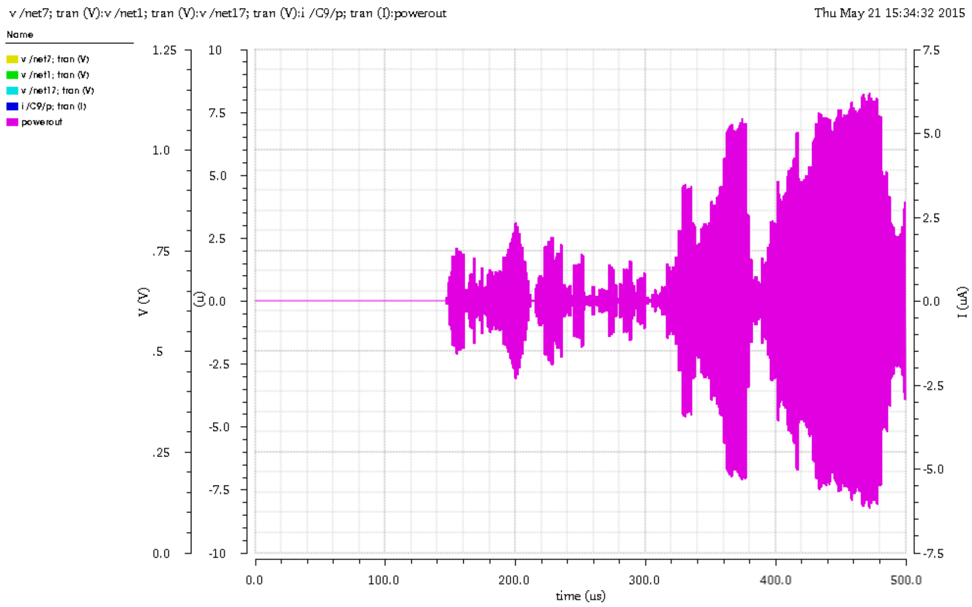


Figure I-83

- f =10MHz

Oscillations

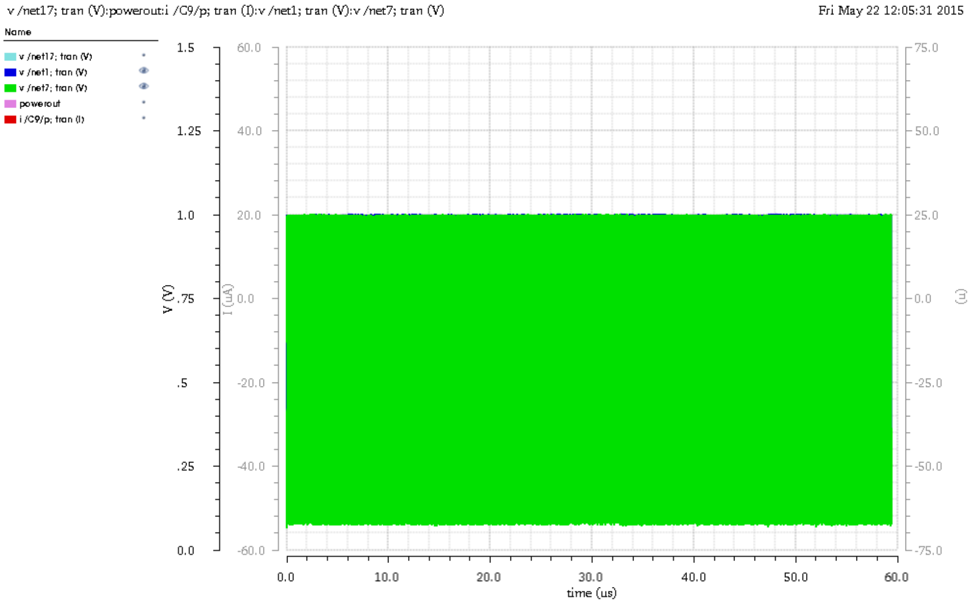


Figure I-84

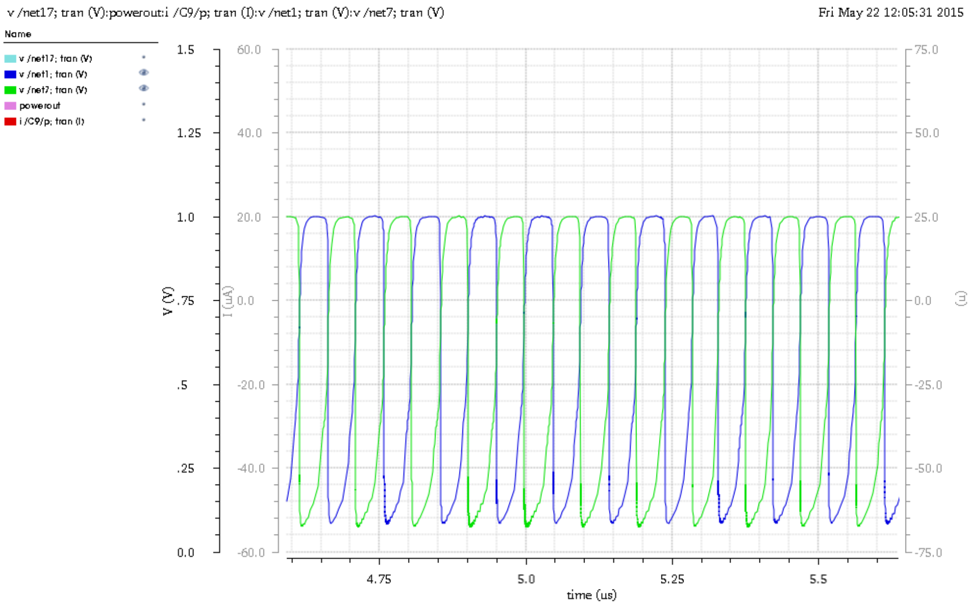


Figure I-85

Output voltage and intensity

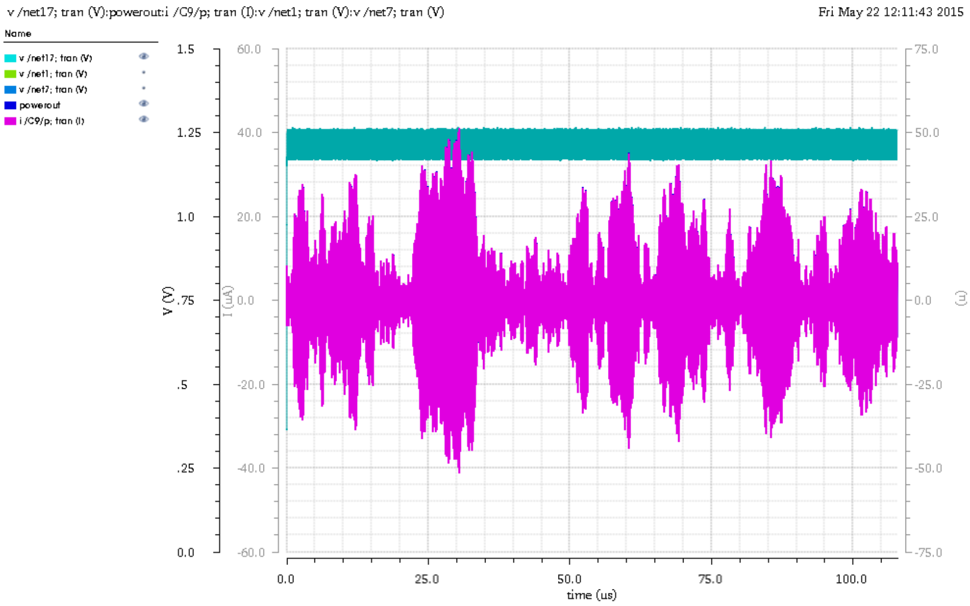


Figure I-86

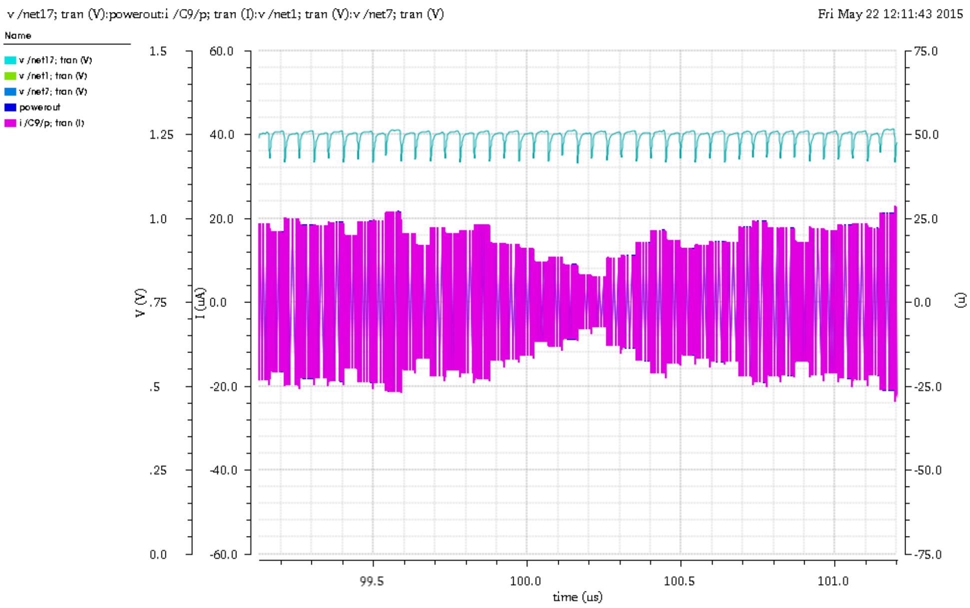


Figure I-87

Output power

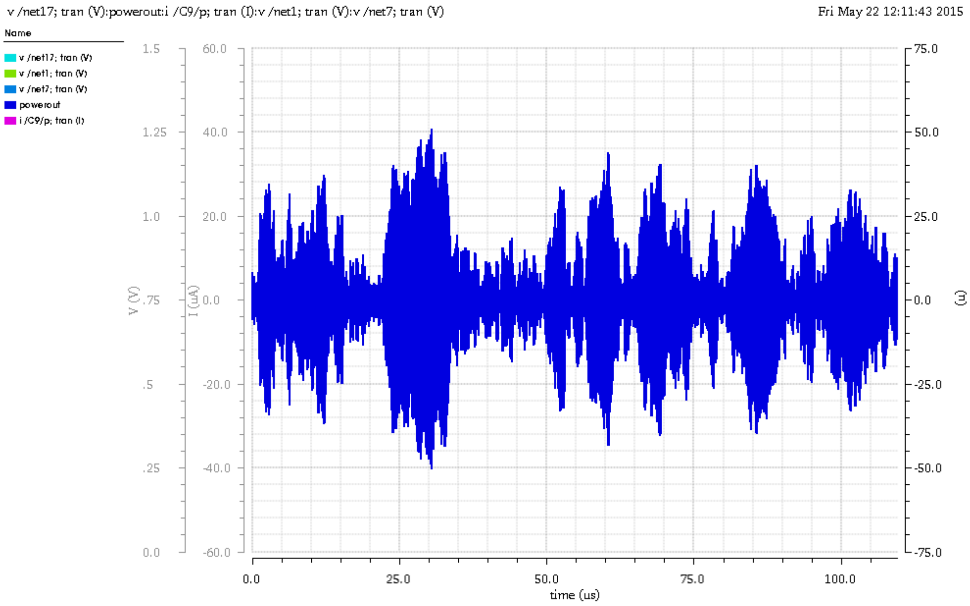


Figure I-88

- f= 50MHz

Oscillations

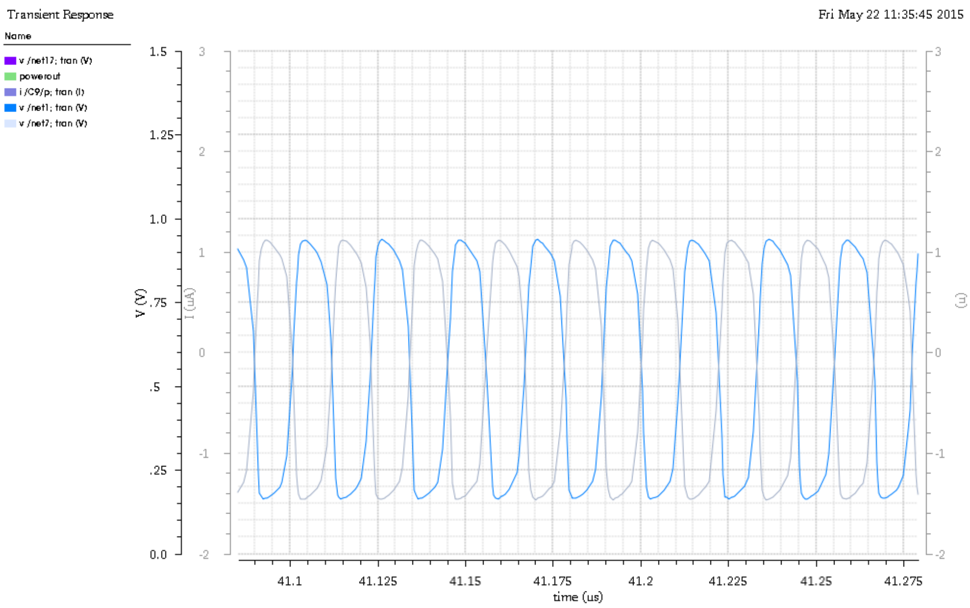


Figure I-89

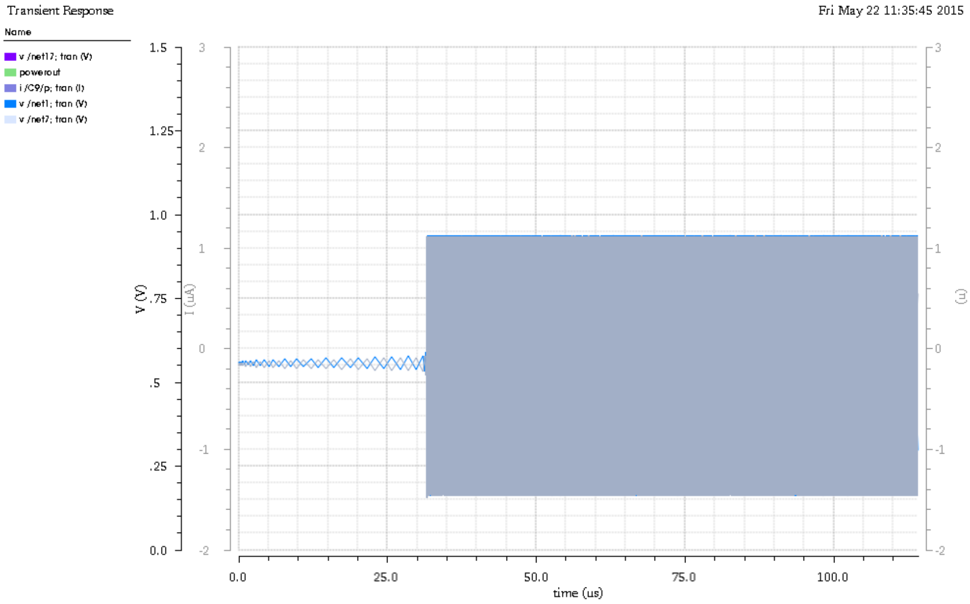


Figure I-90

Output voltage and intensity

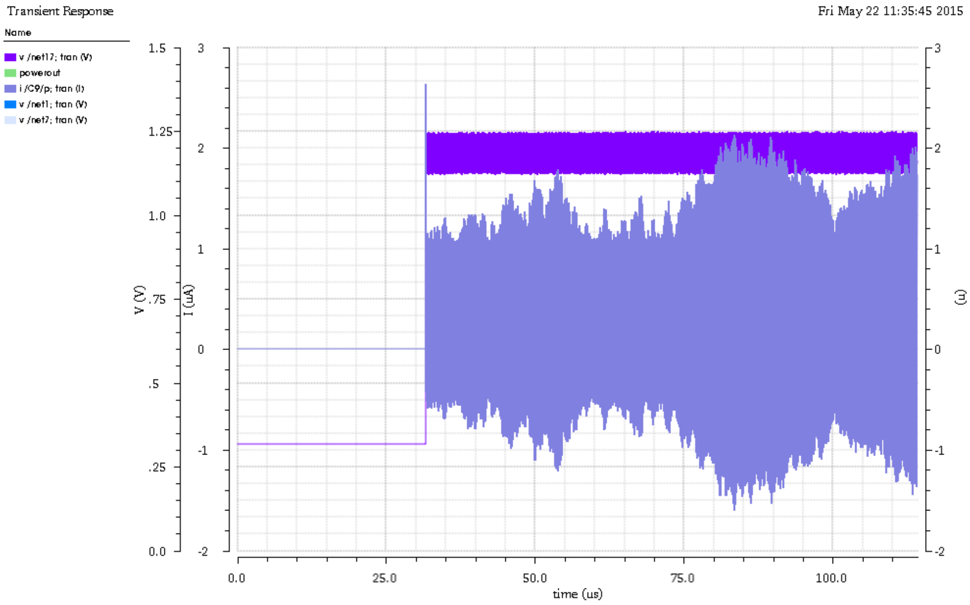


Figure I-91

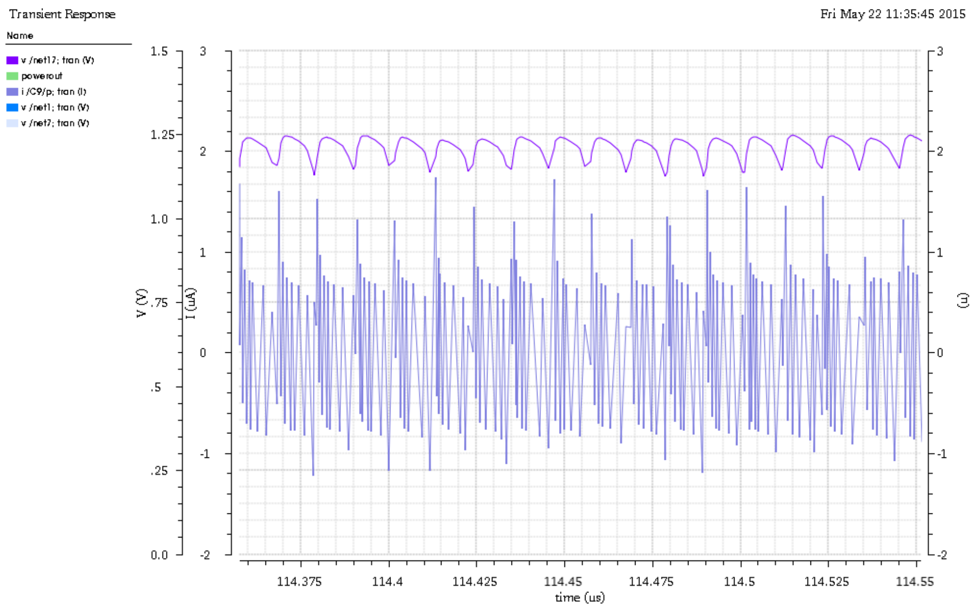


Figure I-92

Output power

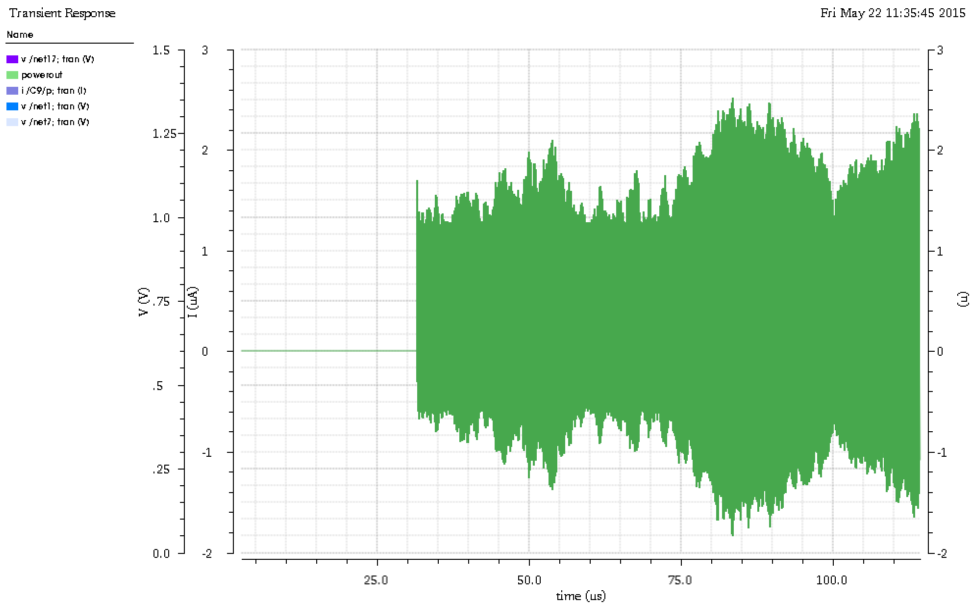


Figure I-93