Building a fast inverter with a BC547

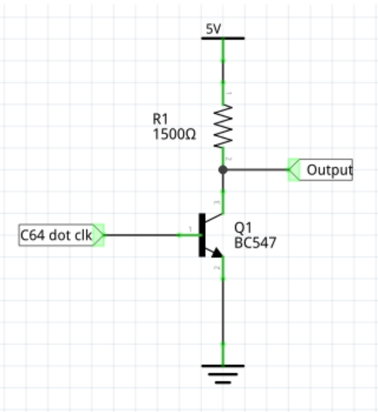
by Daniël Mantione

According to the data sheet, the BC547 has an Ft of 300MHz, which should be plenty in order to build an inverter that can handle multiple MHz. However, as demonstrated by Noël’s Retro Lab, the result in practise may disappoint.

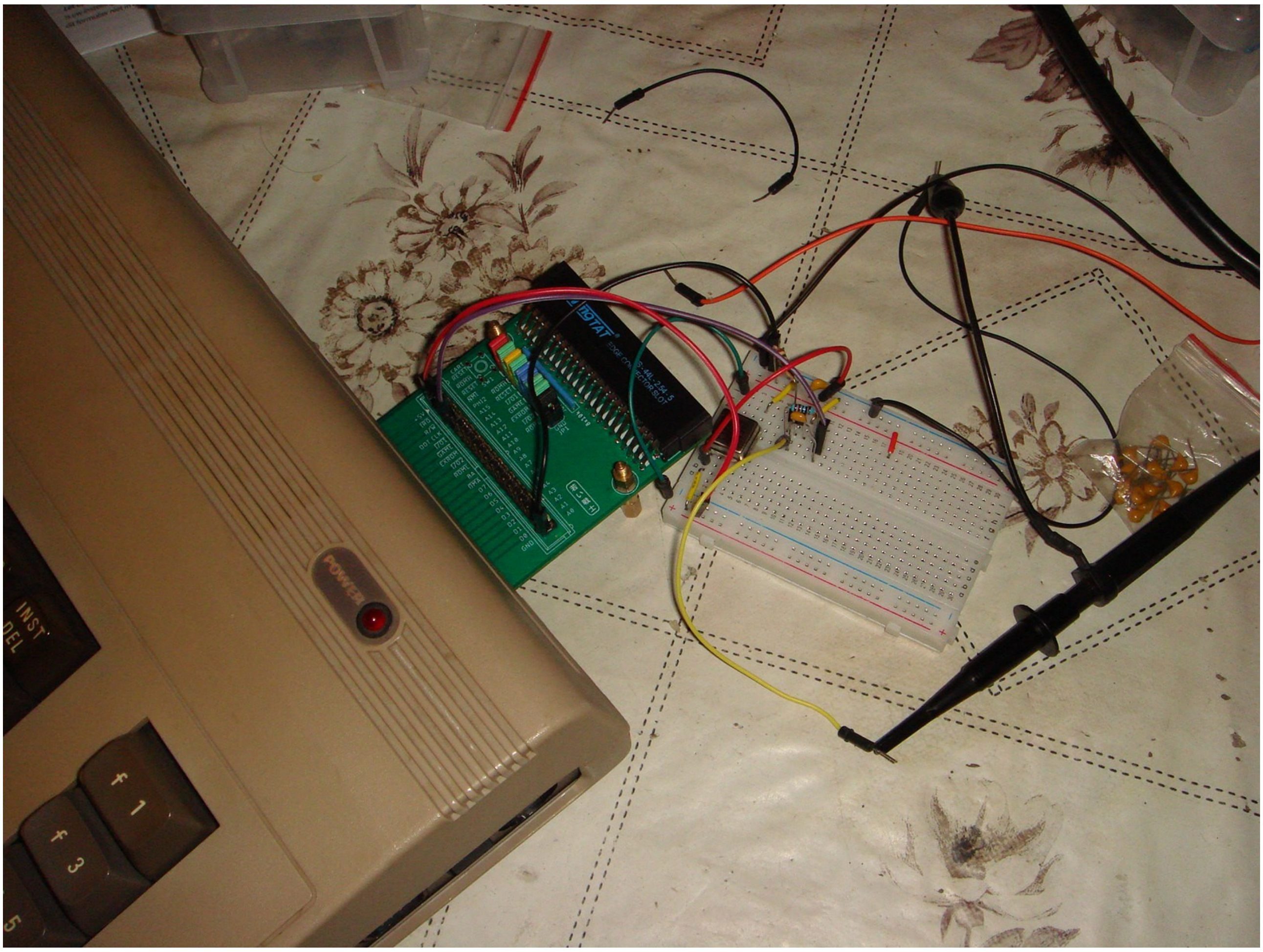
In the Amstrad CPC, the clock signal is dumped directly into a ZTX312 transistor. Can we use a standard BC547?

Why is it important? The reason is the fight against rare parts. The ZTX312 is no longer in production. The 2N2369 was suggested as an alternative, and allthough it is obtainable, it is still a rather exotic transistor, making building your own Amstrad CPC more difficult. If we can build retro computers with as much standard parts as possible, we will benefit the community and increase the availability of hardware. Thus, it is worth some time to check if we can use a standard part. The BC547 is so cheap that you can consider it “free of charge” and therefore is the first transistor you want to consider.

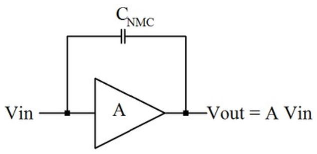
I don’t have an Amstrad CPC or another 4MHz clock, so will use a Commodore 64 and its 8MHz dot clock. That should be fine, if I can generate an acceptable 8MHz signal, a 4MHz signal should be even better. The initial circuit would be like this:



I haven’t tested this: While Amstrad might have been okay to dump a clock signal into the base of a transistor, this won’t work on a Commodore 64, since it will drop the dot clock to ground. The dot clock is primarily used by the VIC-II, so building the above circuit would crash the Commodore 64. Further, although I believe it ain’t harmful (NMOS pull-up is weak), there is no proof the Commodore 64’s clock chip is able to handle the higher currents that will flow.



Why doesn’t dumping the clock into a BC547 work? The answer is the Miller effect. If there is a capacitor between the input and output of an inverting amplifier, the amplifier will not just amplify the signal, but also the capacity of the capacitor, the capacitor will appear to be much larger than it really is:

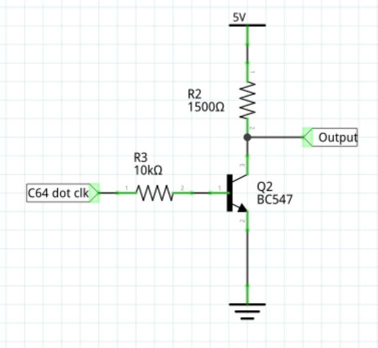


Why is this? Well suppose you amplify the voltage by a factor 2. Then the voltage difference between input and output is also two times as high. With a two times higher voltage you can store twice as much energy in the capacitor, so on the input side, it will appear to be twice as large.

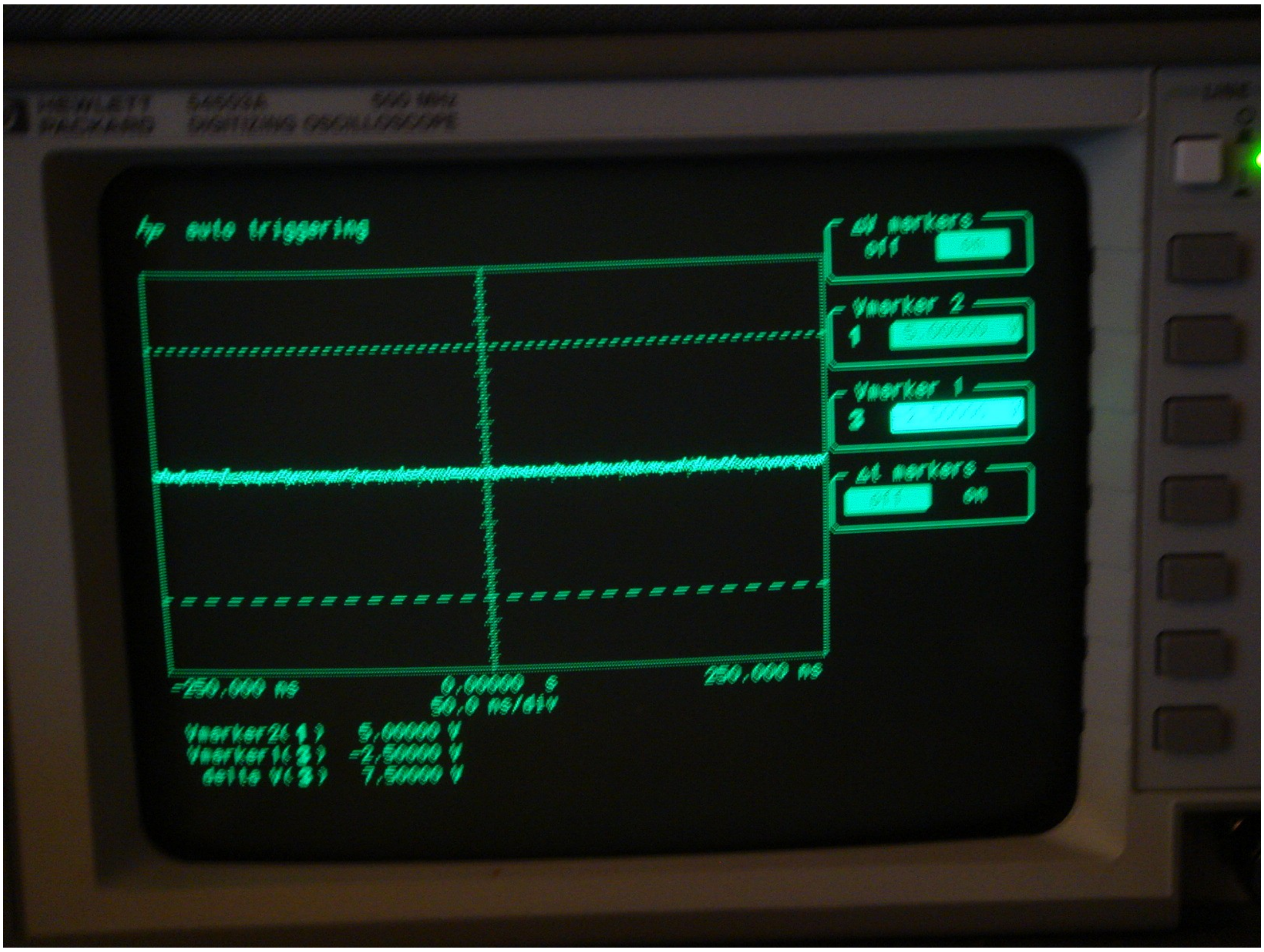
In our case, a BC547 transistor acts as an amplifier. And the parasitic capacitance between base and collector will be amplified a lot by the Miller effect, turning the normally insignificant parasitic capacity into a huge capacitor that will eat away the bandwidth that we can get out of the transistor.

The reason why the BC547 gives problems is that it has a higher amplification factor (Hfe) than the ZTX312 and also slightly higher parasitic capacity. Thus the apparent capacity is way higher than with the ZTX312.

User Helge W did suggest to add a base resistor of 1kΩ-10kΩ. While the current amplification of a transistor (Hfe) is a constant, what counts for the Miller effect is the voltage amplification and this can be reduced by decreasing the current. So the resistor will reduce the amplification and thus allow higher bandwidth:



The idea is good, but it doesn't work. I have built the above circuit and it results in a flat voltage at the output:



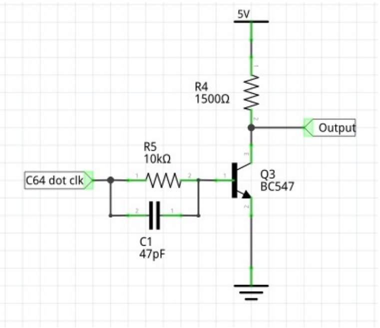
Not even the slightest bit of oscillation is visible!

The reason why the idea doesn't work is that the resistor doesn't just decrease the amplification, it also decreases significantly how fast the input can charge and discharge the parasitic capacitor (which still appears to be much larger than it really is).

How can we mitigate the Miller effect?

Now, if we were building an amplifier for analog signals, according to classic electronics books, we would have to build a cascode circuit. A cascode circuit splits the amplifier between two transistors, so that the parasitic capacitance of the transistor no longer acts as a capacitor between input and output of the amplifier. That requires quite a bit of components.

But we don’t need to amplify analog signals, we just need to build an acceptable inverter. This makes the solution a lot easier. The solution is to add a speedup capacitor over the base resistor:



(The name “speedup capacitor” is a simple translation of how it was called on the forum of the Dutch website circuitsonline.net. I have no idea whether it is the correct English term, however, the name fits its function quite well).

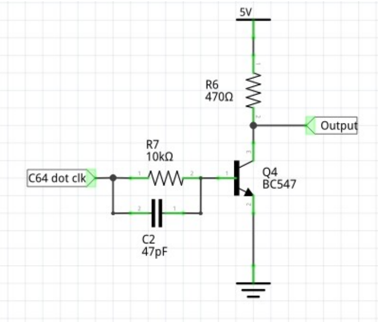
The speedup capacitor allows the input clock to quickly charge and discharge the parasitic capacitor. The capacity of the speedup capacitor should match the apparent Miller capacity. As soon the parasitic capacitor is charged/discharged, the base resistor takes over and sends a current through the transistor. This way, we don’t increase the amplification, but we do allow the input to charge/discharge the parasitic capacitance easily.

This changes the result on the oscilloscope dramatically. Instead of a flat line, we now get an 8MHz clock signal! However, it still doesn’t look like a nice square wave:

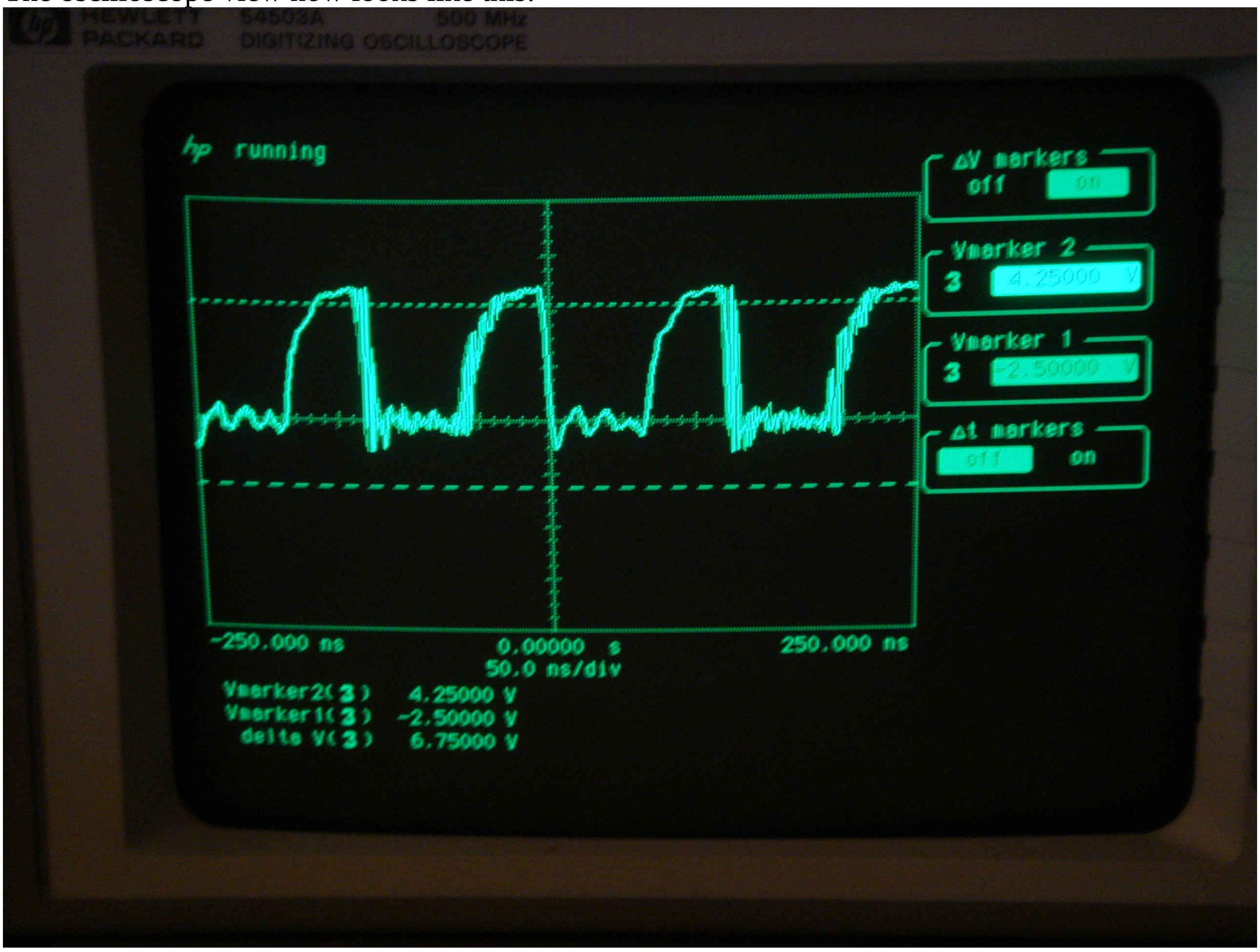
There is quite a bit of undershoot, the signal also rises beyond 5V. And the signal rise time is a bit slow.

I believe the under/overshoot is caused by the fact that my 47pF capacitor still isn't large enough. When the input pulls on the output via the parasitic Miller capacitor, the voltage is pulled below 0V. We could try an even larger capacitor. However, I don't have anything useful available at the moment and there is also a limit how much capacity I want to connect to the C64's clock line.

However, there is another way we can improve the signal: Decrease the resistor at the collector of the transistor. This results in a "counter force" for the voltage to drop below 0V and also will make the voltage rise faster. Let's reduce the resistor to 470Ω:



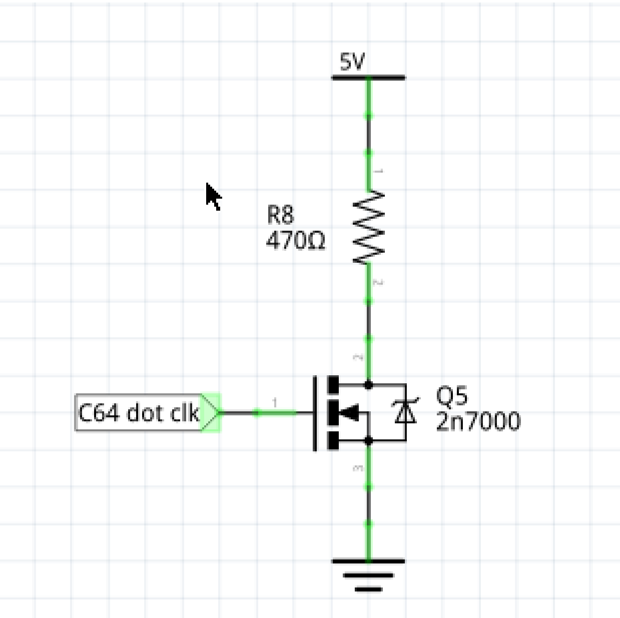
The oscilloscope view now looks like this:



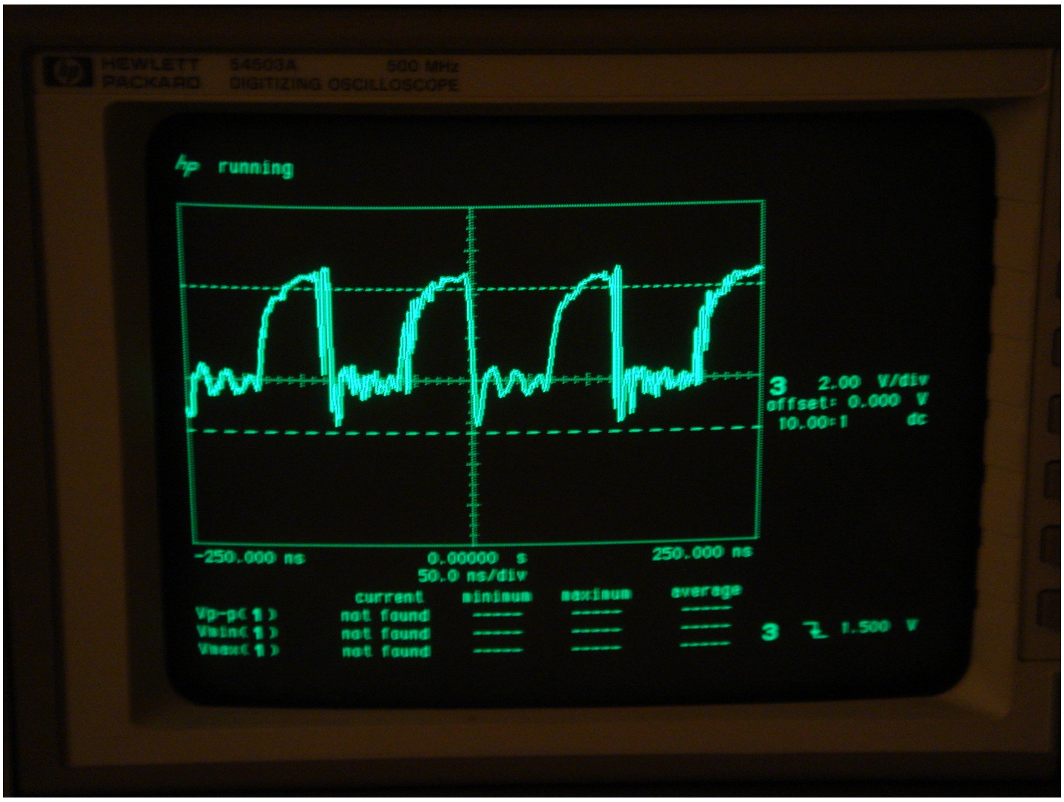
… and this looks like an acceptable 8MHz clock signal to me.

The BC547 in my experiments was a BC547B. A BC547A has a smaller amplification factor and thus a smaller Miller effect. It might be beneficial to help getting an even better clock signal. However… I don’t have a BC547A, but it is still a standard part available everywhere.

In the Youtube comments, my own suggestion was to use a 2N7000 MOSFET. A MOSFET isn’t immune from the Miller effect, but has the advantage that no base resistor is needed and therefore the input can use all the power it has available to charge and discharge the imaginary Miller capacitor:



I did test the above circuit and was happy to see that it indeed creates a very acceptable 8MHz clock signal:



The MOSFET solution is IMO by far the most elegant solution, since it doesn’t require charges to the PCB and therefore allows the replica to be a replica. Just like the BC547, the 2N7000 is a super standard part that can be bought anywhere.

However… if uniformity of components is desired (BC547 was also used elsewhere in the board), the use of a base resistor and speedup capacitor can still be a good solution.