Bilkent University

EE-202 Circuit Theory

Lab 2

Voltage Spike Generator

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Section 02

Introduction

The purpose of this lab is to design a passive linear circuit to generate high voltage spikes from 10V peak-to-peak square wave with a source resistance of 50Ω and frequency less than 5MHz. The peak value of the voltage spikes (Vp) must be 15V ≤ Vp ≤ 25V. Full width at half maximum (FWHM), must be less than 80ns (Δt < 80ns). Figure 1 shows the required input and output plot.

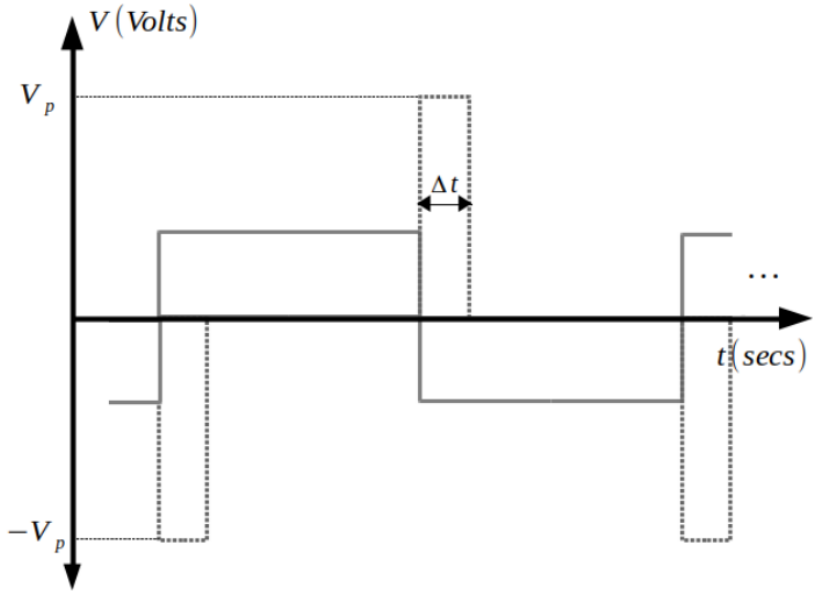

Figure 1: Expected output voltage plot

Analysis

Inductors can be used in the circuit to achieve a voltage spike whose duration is very short. The voltage of an inductor is expressed as:

$$V_L = L\frac{di_L}{dt} \tag{1}$$

where L is the inductance and i_L is the inductor current. Hence the current can be expressed as:

$$i_L(t) = i(0) + \frac{1}{L}\int_0^t V(a)da \tag{2}$$

When a simple circuit, with a voltage source V_S and an inductor L, is considered with a switch open at t=0, both the current and the voltage is zero for the inductor at that time. When the switch is closed, the voltage of L changes to V_S. Putting this value at (2), and considering that V_S is constant, we obtain:

$$i_L(t) = \frac{V_S}{L} t$$

(3)

And when the switch is opened again, the current decreases from the reached value to zero. Using (1), it can be seen that the voltage should go to infinity. However, since inductor current $i_L(t)$ is a continuous function, it cannot change instantaneously, hence causing voltage spikes to occur [1].

To control the output voltage obtained, a transformer can be used. A transformer is essentially two inductors coupled by being connected to a core. Figure 2 shows the model of a transformer.

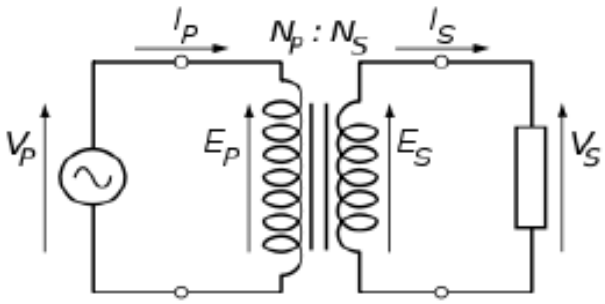

Figure 2: Transformer circuit

The relationship between the voltages, currents and the number of turns (N) can be expressed by Faraday's Law of Induction as:

$$\frac{N_p}{N_s} = \frac{V_p}{V_s} = \frac{I_s}{I_p}$$

(4)

And to express the relationship between the inductance L and the turn number N:

$$L = A_L * N^2$$

(5)

where A_L is the inductance per turn of the toroidal core. Using (4) and (5);

$$\frac{L_p}{L_s} = \left(\frac{V_p}{V_s}\right)^2$$

(6)

Considering that peak value of the input voltage is 5V (input's peak-to-peak value is 10V) and output's peak value should be 15V ≤ Vp ≤ 25V, the voltage ratio should be between 5/15 and 5/25, hence the inductance ratio should be between 1/9 and 1/25 by (6). For this lab L_p is chosen as 1 μH and L_s is chosen as 9 μH. To calculate the number of turns to wind the inductors:

$$N_p = \sqrt{\frac{L_p}{A_L}} = \sqrt{\frac{1\ \mu\text{H}}{20\ nH/turns^2}} \cong 7$$

$$N_s = \sqrt{\frac{L_s}{A_L}} = \sqrt{\frac{9\ \mu\text{H}}{20\ nH/turns^2}} \cong 21$$

(7)

since A_L=20 nH/turns^2 for the T38-8 core used to wind the inductor. For the load resistor, 2.2 kΩ is chosen. As for the input voltage's frequency, 1 MHz is chosen. Then the circuit is implemented on LTSpice.

Simulations

The implemented circuit can be seen in Figure 3. Input voltage is a 10 V peak to peak square wave with 50Ω source resistance and 1 MHz frequency.

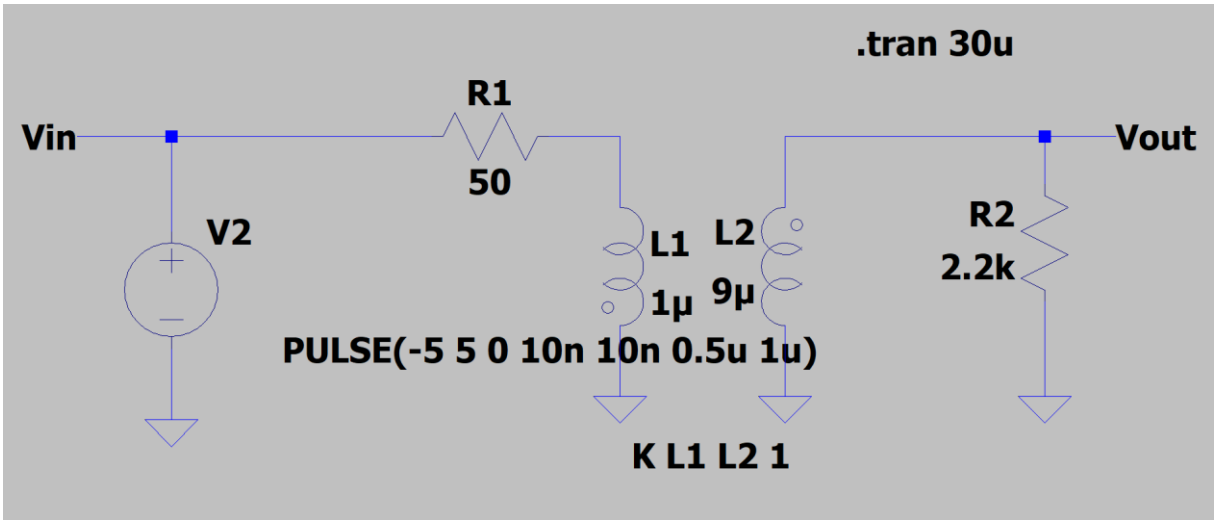

Figure 3: Proposed circuit in software

The output voltage can be seen in Figure 4. The waveform has a spike shape as expected. The peak value of voltage spikes (Vp) is 20.3 V, which is between 15 V and 25 V, and the full width at half maximum (FWHM) is approximately 22.6 ns, which is less than 80 ns. The spike duration therefore is much shorter than the input voltage period, which is 1 μs. Hence the conditions are satisfied with this circuit. Measurements can be seen in Figures 5-6, and the results are presented in Table 1.

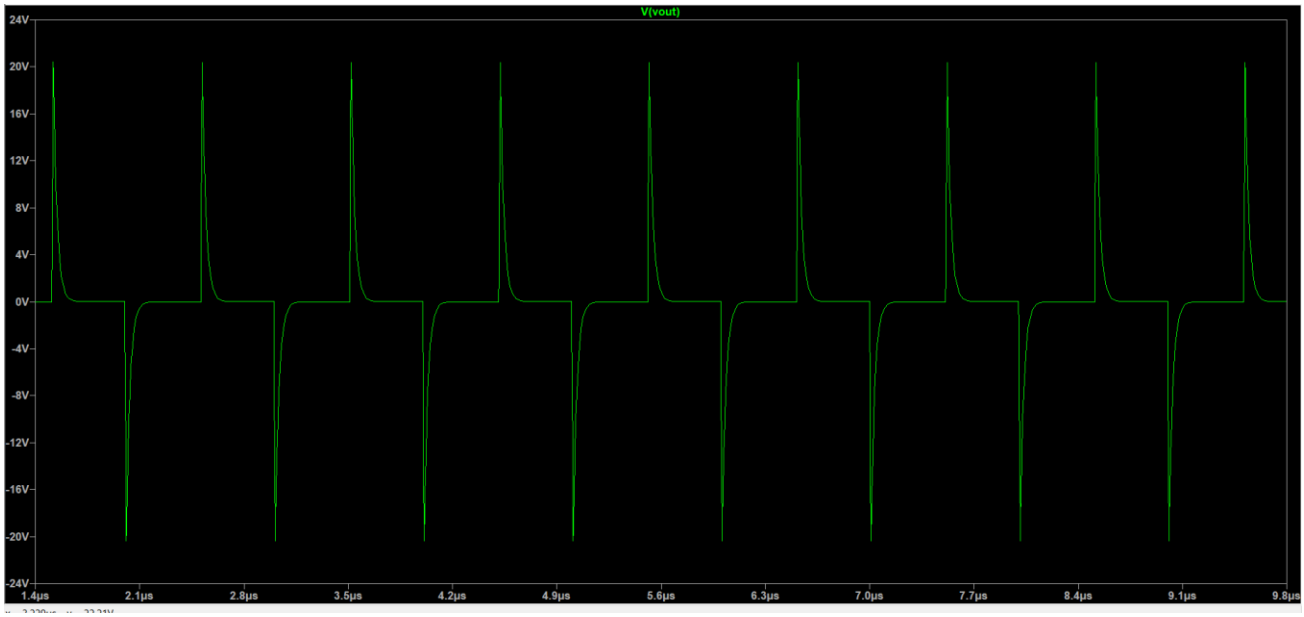

Figure 4: Output voltage spikes

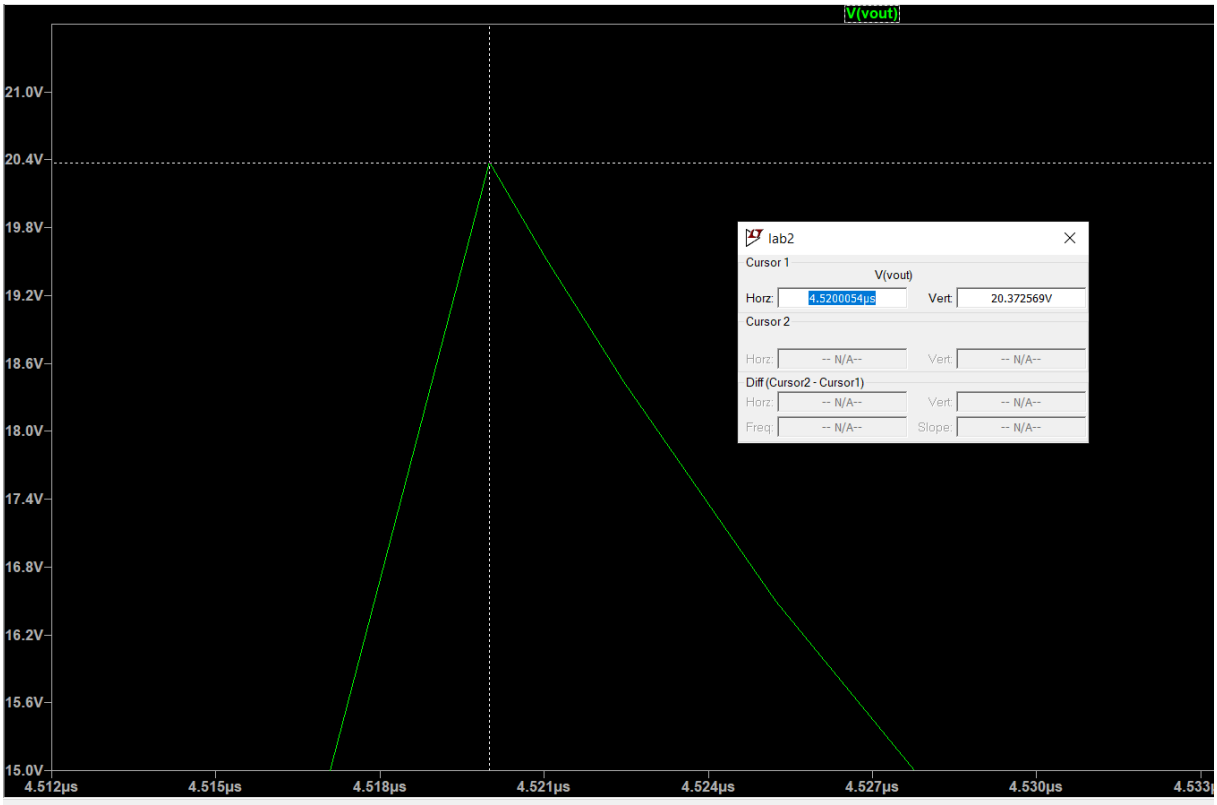

Figure 5: The peak value of voltage spikes (Vp) is 20.3 V

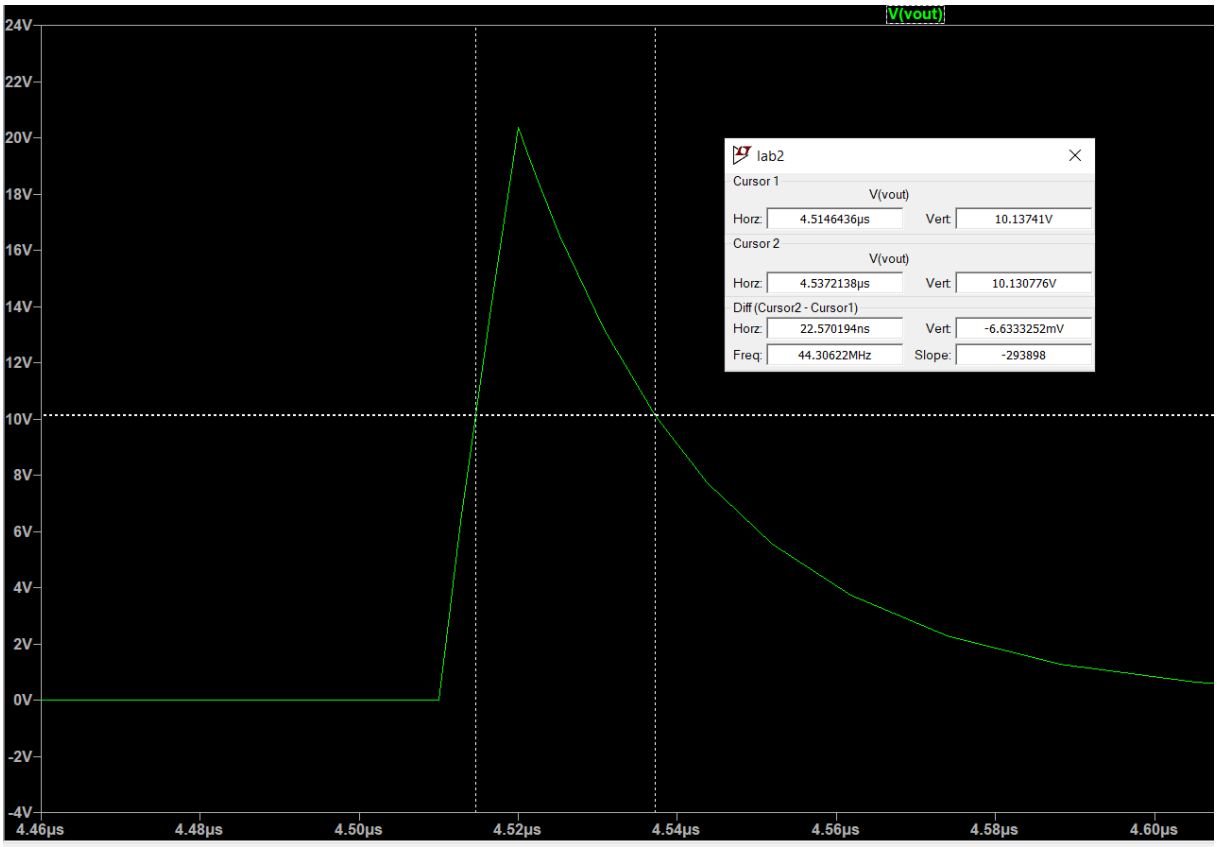

Figure 6: The FWHM is 22.6 ns

Input peak-to-peak voltage (Vin)	Input frequency	Output peak voltage (Vp)	Full width at half maximum (FWHM)
10 V	1 MHz	20.3 V	22.6 ns

Table 1: Simulation results

Hardware Implementation

First the fall, rise times and peak value of the input voltage are measured by connecting a 47Ω resistor across the terminals of the signal generator, as seen in Figure 7. The rise and fall times are 17.8 ns and 18 ns respectively, and the peak voltage is 4.64 V. Figures 8-10 show the measurements on the oscilloscope.

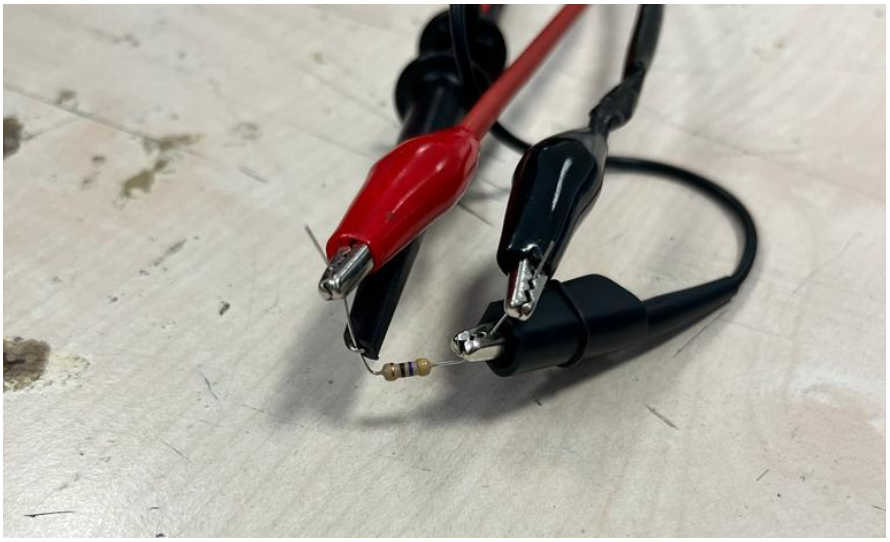

Figure 7: 47 Ω resistor connected to the terminals

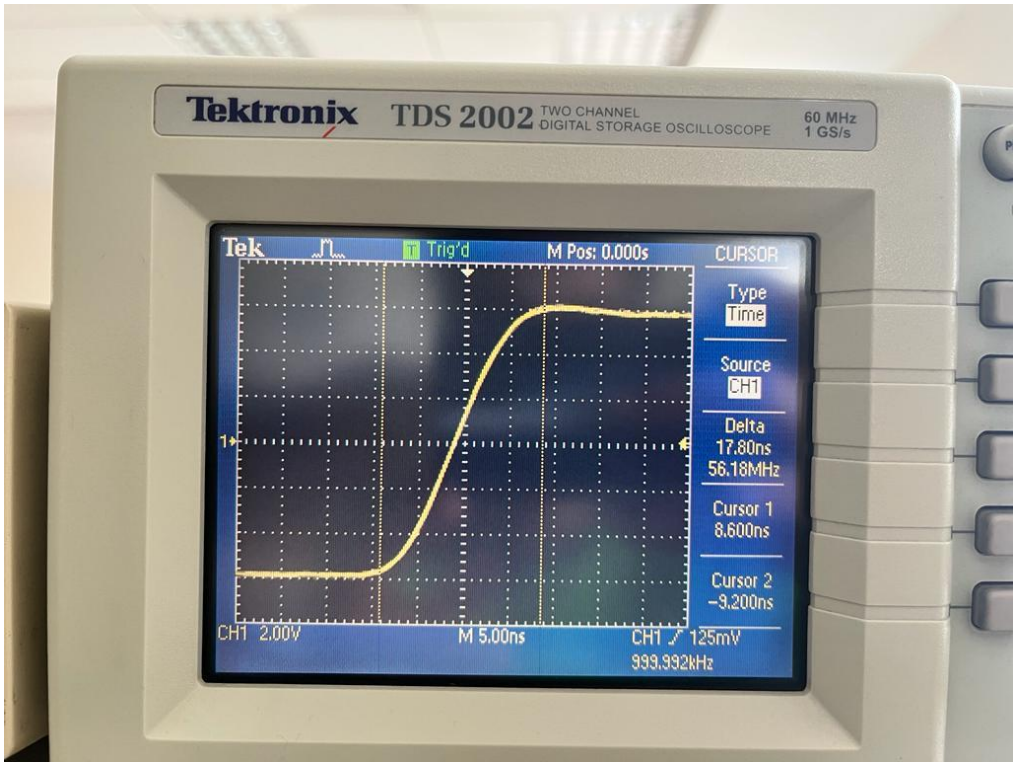

Figure 8: Rise time is measured as 17.8 ns

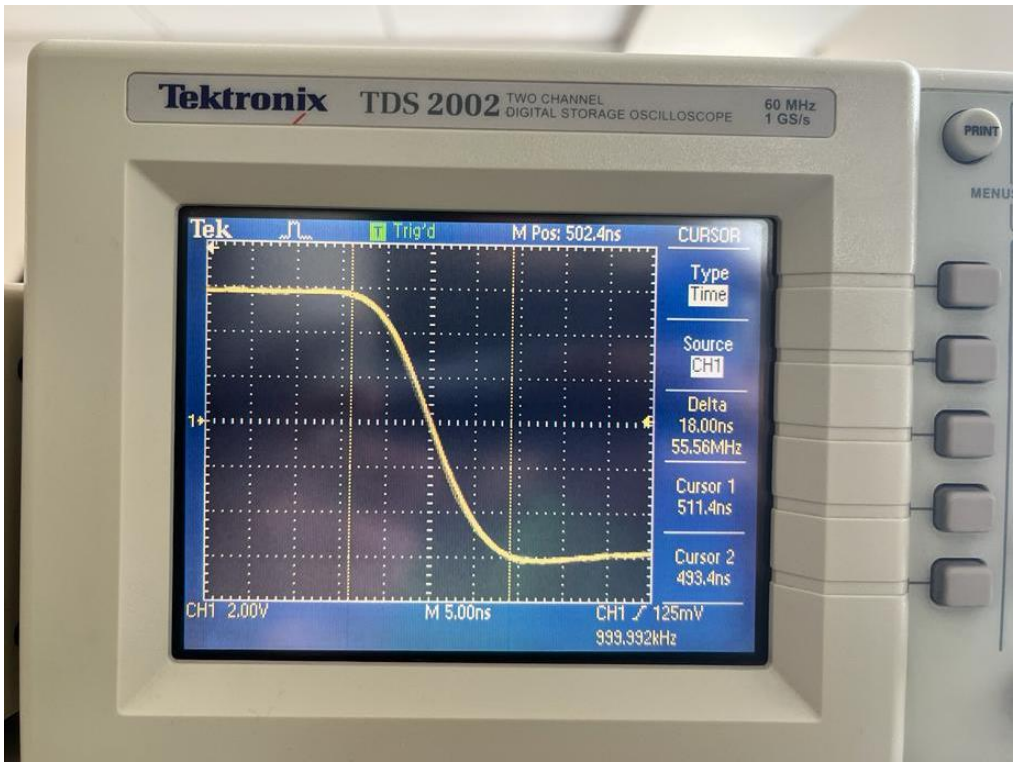

Figure 9: Fall time is measured as 18 ns

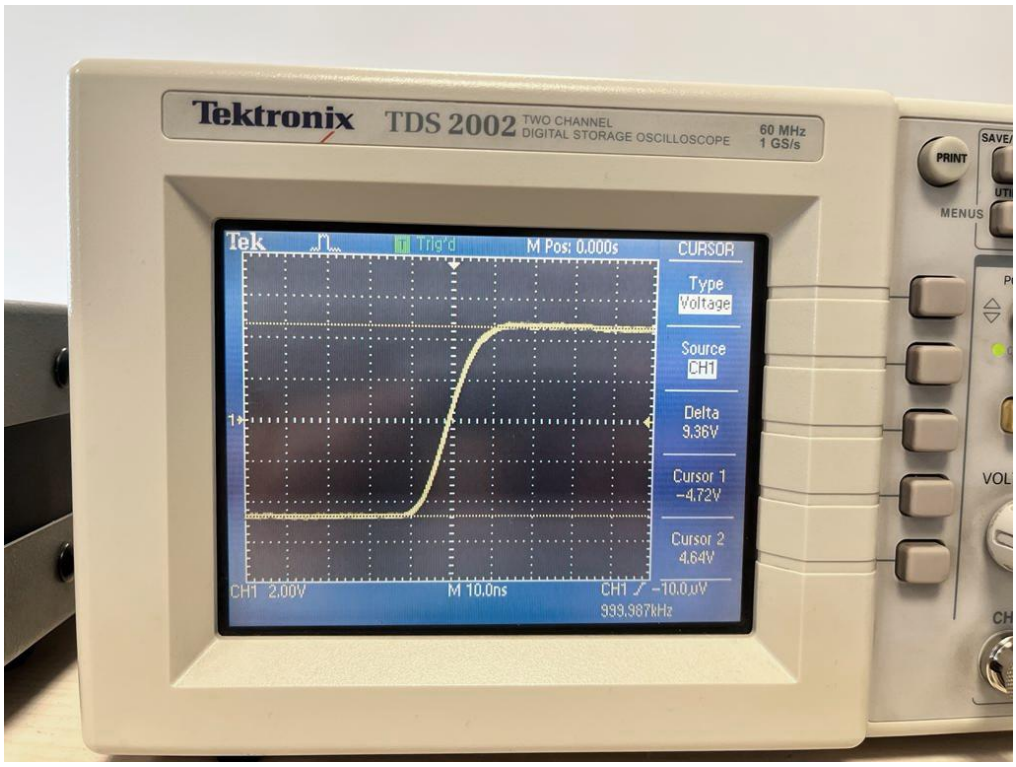

Figure 10: Peak voltage is measured as 4.64 V

Then the circuit is implemented. First the inductors are winded around the T38-8 core. To match the software circuit, the primary was winded with 7 turns and the secondary was winded with 21 turns, as calculated above. Then the resistors and the voltage source are connected. Figure 11 shows the circuit.

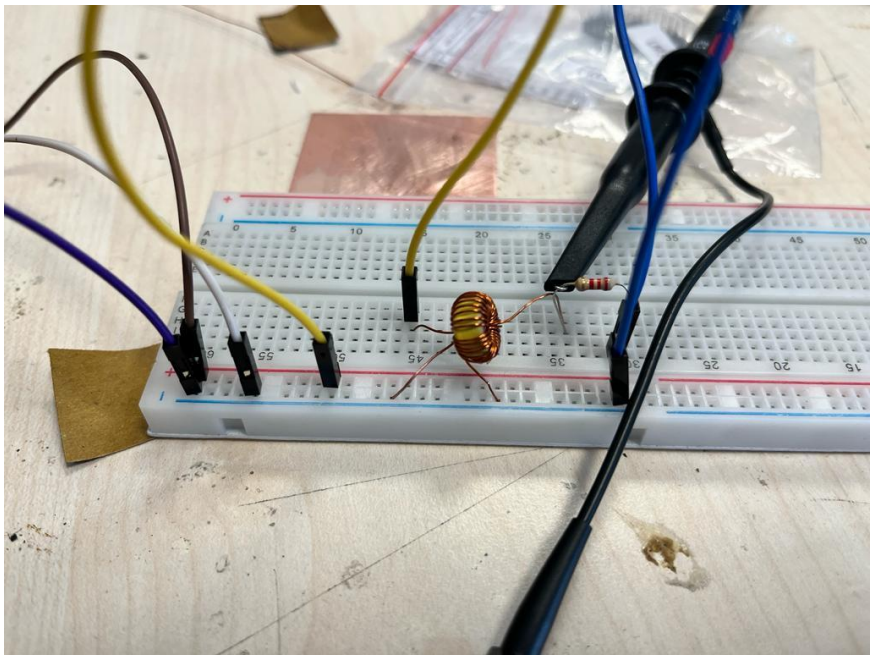

Figure 11: Circuit is implemented on the breadboard

After that, the output waveform is observed and the measurements for peak voltage and full width at half maximum are made, as seen in Figures 12-14. The results for all measurements are presented in Table 2, along with the error percentages with respect to the software results.

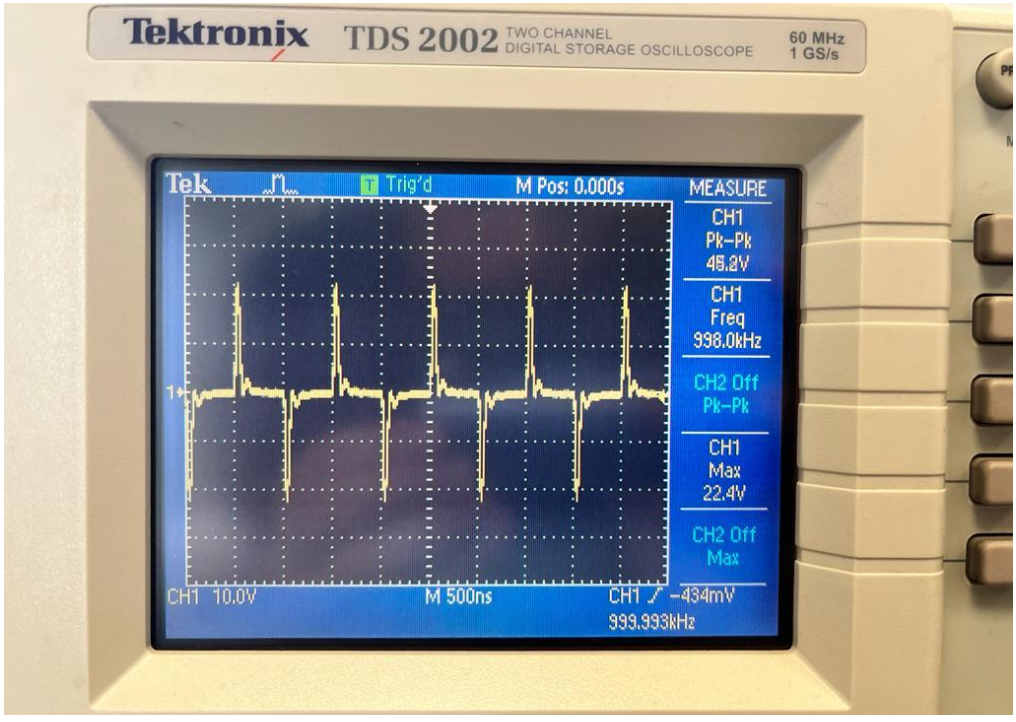

Figure 12: Output waveform, the peak voltage is 22.4V

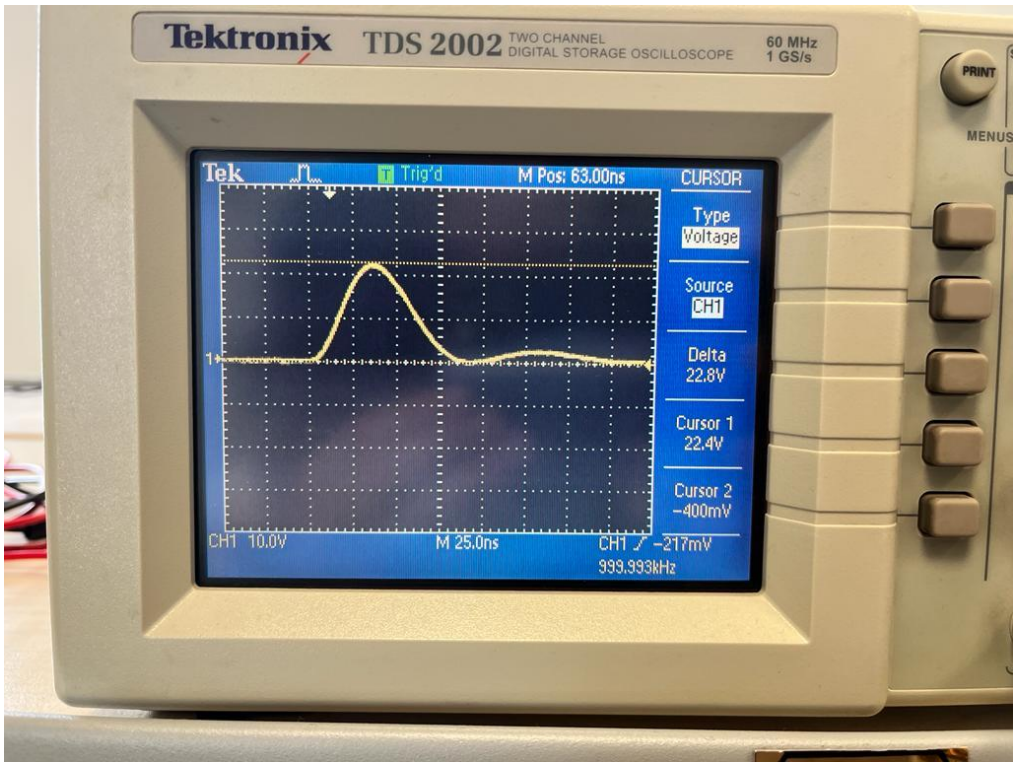

Figure 13: The peak voltage is 22.4V

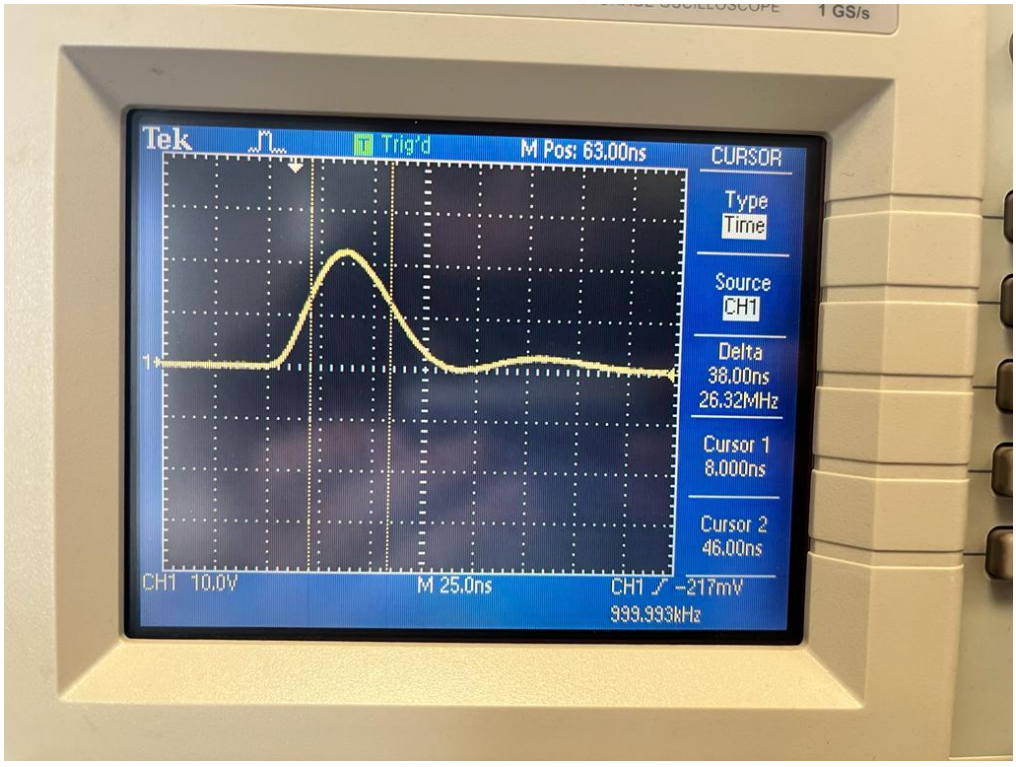

Figure 14: The FWHM is 38 ns

Rise and fall times of voltage source	Input peak voltage	Measured output peak voltage (Vp)	Error percentage for Vp	Measured full width at half maximum (FWHM)	Error percentage for FWHM
17.8 ns, 18 ns	4.64 V	22.4 V	10.34%	38 nH	68%

Table 2: Hardware results

For the hardware implementation, the peak voltage of the spike was 22.4 V, which is between 15 V and 25V, and the FWHM was 38 nH, which is less than 80 nH. So, the hardware results also conform to the conditions for the circuit.

Conclusion

The software and hardware results for peak voltage Vp and the FWHM matched with 10.34% and 68% percentage errors. The reason for these errors can be the inner resistances and leakage inductances of the transformer in the HW lab. Unlike the simulations, in real life, wires have inner resistances and the transformers therefore have leakages. Also, measurements for FWHM involve very small numbers in nanoseconds, so measuring those can cause high measurement errors.

Still, both the software and hardware results are in the required intervals. The phenomenon used to implement the circuit is “inductor kickback” [1], which is caused due to the continuity of inductor current. Since it can’t change instantaneously, it causes voltage spikes to occur. To control the spike’s peak voltage, a transformer circuit is implemented, which involves essentially two inductors. Despite the errors between the software and hardware implementations, they both satisfy the requirements.

Overall, this lab helped to demonstrate the behavior of inductors and transformers. It also taught how to implement a transformer both on LTSpice and on hardware using toroidal cores. With this lab, it is observed how non-ideal components act in real life, in this case, they cause voltage spikes.

References

[1] W. McAllister, “Inductor kickback,” Spinning Numbers, https://spinningnumbers.org/a/inductor-kickback.html (accessed May 9, 2023).