



PAPER

Flattening the oscillations of an underdamped RLC circuit using a diode

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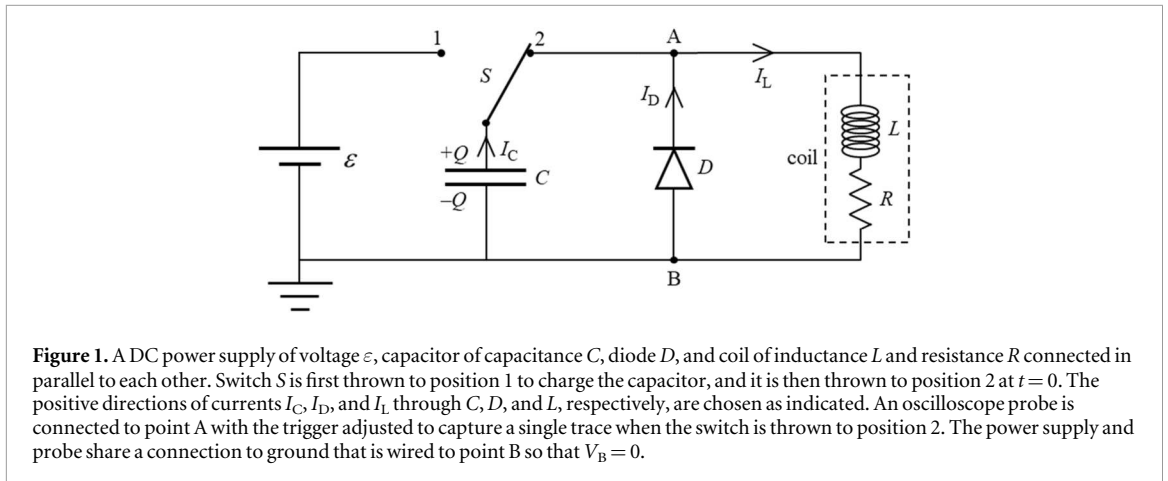
E-mail: mungan@usna.edu**Keywords:** diode, RLC circuit, Kirchhoff's laws, oscilloscope measurements, hysteresis**Abstract**

An electromagnetic oscillator results when a charged capacitor and a coil are wired together. Suppose a diode is now additionally connected across these two circuit components in parallel. If the diode starts out reverse biased relative to the capacitor, then a negligible current will initially flow through it. Hence, charge will flow off the capacitor during the first quarter cycle of oscillation and the current through the coil will build up to a maximum. Shortly thereafter, the diode will turn on and essentially short out the capacitor. Ideally, a constant current will subsequently flow through the diode and coil. In reality, however, the resistance of the coil will cause that current to slowly decay, the voltage across the diode will drop below its forward turn-on voltage, and RLC oscillations of the capacitor and coil will resume. Experimental measurements are performed to verify this behavior for an air-core coil. The results are shown to reasonably fit the theory if the familiar Shockley exponential equation is used to model the current–voltage characteristic of the diode. Poor agreement between measurements and predictions are obtained, however, if an iron-core coil is used, primarily owing to dissipation by hysteresis. The concepts presented here are accessible to undergraduate physics students at the point in the curriculum that they are introduced to semiconductor electronics.

1. Introduction

The study of electrical circuits consisting of discrete analog elements such as batteries, resistors, and capacitors—both theoretically using Kirchhoff's laws and experimentally in a student laboratory—is a critical component of an introductory undergraduate course in electricity and magnetism. It would probably not be exaggeration to say that the very concepts of resistance, capacitance, and inductance will not be understood by students until they are used concretely in circuits. If and when diodes are introduced, as in a modern physics course, their key job of *rectification* is likewise best appreciated in the context of specific circuits. Such rectification can be illustrated, for instance, by clipping off the negative peaks of an oscillating signal [1]. That can be accomplished by putting a single diode *in series* with an LC oscillator. In contrast, the present article considers what happens if a diode is instead placed *in parallel* with a capacitor-coil pair. The interesting result is that full (rather than half) cycles of oscillation (specifically an indefinite number for ideal components, but at least a few complete periods for real components) get replaced by an approximately steady current. The circuit remains simple, making it attractive for theoretical analysis and experimental investigation in an intermediate-level undergraduate course.

Introductory physics textbooks [2] analyze the undriven RLC circuit as the electromagnetic analog of a mass attached to a Hookean spring and moving through a viscous fluid. Provided the total circuit resistance R is not too large, the result is underdamped oscillations as charge $\pm Q$ alternately flows on and off plates of capacitance C in the form of current $\pm I$ flowing in a coil of inductance L . Later, in the modern physics portion of the textbook, diodes are introduced as the simplest example of a semiconductor device. That discussion usually begins with the most basic form of diode, often called a *signal diode*, which can be thought of as a one-way valve



permitting current to flow in a single direction only, to be distinguished from Zener, tunnel, Schottky, light-emitting, and other forms of diodes designed for more specialized applications. Several methods in educational journals have been proposed to measure key properties of diodes, including their resistance, ideality factor, thermal behavior, knee voltage, and bandgap energy [3–7]. If an RLC circuit is driven by a sinusoidal voltage source, a resonance curve results as the source frequency sweeps over the LC oscillational frequency [2]. Perhaps surprisingly, the capacitor C in such a circuit can be replaced by a reverse-biased diode [8].

2. Theory

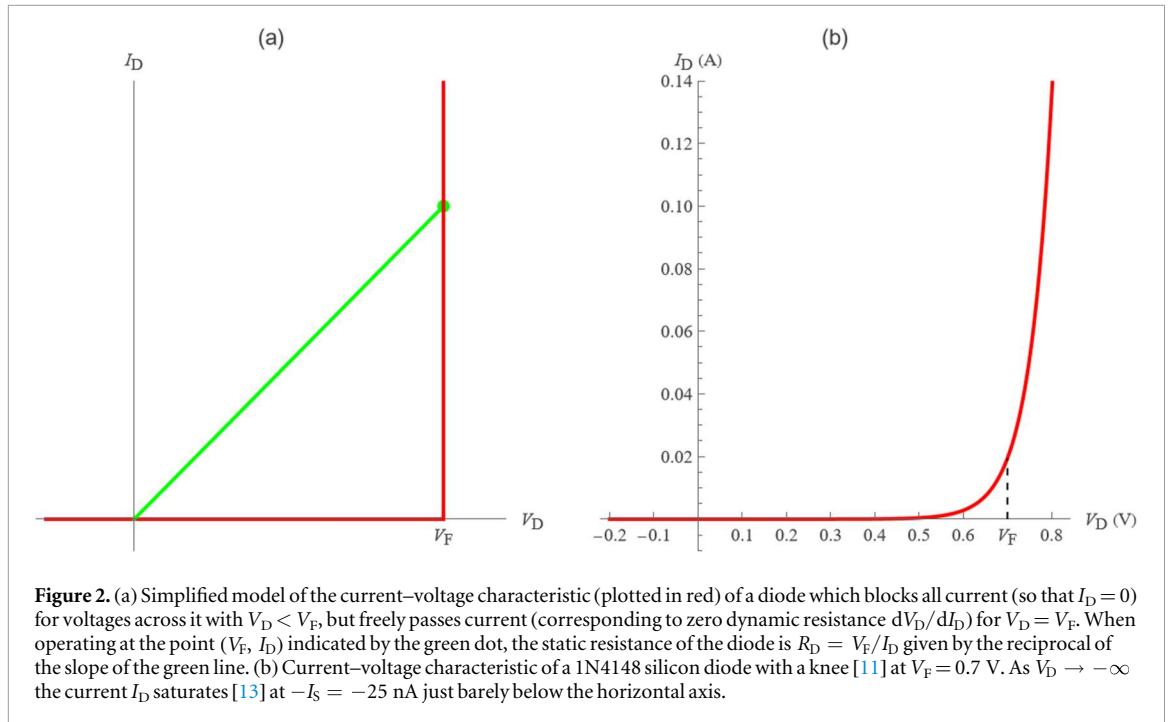
A pedagogically instructive way to explore the properties of a signal diode is to connect it across the capacitor of an underdamped RLC circuit. The forward direction of the diode is oriented opposite to the initial polarity of the charged capacitor in order to avoid immediately shorting it out. The circuit diagram is in figure 1. Putting $R = 0$ reproduces the sketch in Cross [9]; alternatively, removing the capacitor C and replacing the single-pole double-throw switch S with a single-pole single-throw switch between points 1 and 2 reproduces figure 5 in Leu [10]. Referring to the two points labeled A and B, positive voltage across the diode is defined as the potential difference $V_D = V_B - V_A$, whereas positive voltage across the capacitor is defined as $V_C = V_A - V_B$.

One can helpfully understand the circuit by making successively better approximations to it. Start by modeling the current–voltage characteristic of the diode as a simple one-way valve, passing forward current $I_D > 0$ with zero resistance for forward biasing V_D infinitesimally greater than zero, but completely blocking all backward current $I_D < 0$ with infinite resistance for any reverse biasing $V_D < 0$. The capacitor starts out (at time $t = 0$) charged to $Q_0 = C\varepsilon$ at the instant that switch S is flipped from position 1 to 2. Since the diode is initially reverse biased (with $V_{D0} = -V_{C0} = -\varepsilon$), the current through it is zero (i.e. $I_D = 0$) and thus $I_C = I_L$. If $R = 0$, the circuit will begin to perform undamped charge oscillations [2] of the form $Q(t) = Q_0 \cos \omega t$ with angular frequency $\omega = (LC)^{-1/2}$. After a quarter of a period (at $t = T/4 = 0.5 \pi/\omega$), the charge Q and hence the capacitor voltage V_C will cross through zero and start going negative. Consequently the diode voltage $V_D = -V_C$ will start going positive, so that the diode will act like a short. However, at $t = 0.5 \pi/\omega$ the current through the coil will have reached a maximum value of $I_{L \max} = I_{C \max} = -\dot{Q}_{\max} = Q_0 \omega$, where overdots denote time derivatives and the minus sign arises because the (positive) direction of current I_C in figure 1 corresponds to a decrease in charge Q on the positive plate of the capacitor. The inductance will thereafter indefinitely maintain that same current flowing clockwise through the right-hand loop of the circuit consisting of the coil and diode.

At the next level of approximation, the diode can be modeled as having a turn-on voltage equal to the forward threshold voltage $V_F > 0$, as illustrated in figure 2(a). For a silicon diode at room temperature, the knee V_F is found experimentally [11] to be 0.7 V. Suppose the current I_D through the diode on average equals half the maximum value of $I_{D \max} = Q_0 \omega = C\varepsilon(LC)^{-1/2}$ through the coil. More exactly (while still neglecting R in figure 1), however, it decays with an average time constant of $\tau = L/R_D = L(0.5I_{D \max})/V_F$, using the formula for the diode resistance R_D given in the caption of figure 2. The ratio of that time constant to the period of oscillations is then

$$\frac{\tau}{T} = \frac{\varepsilon}{4\pi V_F} \quad (1)$$

assuming $\varepsilon \gg V_F$ so that the decay is slow. This ratio approximates the range (in periods) over which a current will flow through the diode from point B to A in figure 1, after which the diode will again shut off and LC oscillations of the circuit will resume.



Finally, a more realistic model of the IV characteristic of the diode than that sketched in figure 2(a) has a knee at V_F , with the curve at higher forward voltages rising sharply but not infinitely sharply, while at voltages $V_D < V_F$ the curve has a small but nonzero slope and passes through the origin. The Shockley diode equation expresses these ideas mathematically in terms of an exponential function as

$$I_D = I_S[\exp(V_D/V_T) - 1] \quad (2)$$

where $V_T = 2kT/e$ is the thermal voltage including the ideality factor of 2 for silicon diodes [12]. Here T is room temperature (in K), k is the Boltzmann constant, and e is the elementary charge, so that $V_T = 51.6$ mV. The reverse saturation current for the 1N4148 diode [13] used below is $I_S = 25$ nA. Given these parameters, equation (2) is plotted in figure 2(b).

The circuit in figure 1 can now be analyzed using Kirchhoff's laws. The current junction rule applied at either point A or B implies

$$I_L = I_C + I_D. \quad (3)$$

Going clockwise around the loop consisting of the capacitor and diode, the voltage loop rule becomes

$$Q/C + V_D = 0 \quad \Rightarrow \quad I_C = C\dot{V}_D \quad (4)$$

by taking a time derivative to get the second equality. Likewise, the time derivative of equation (2) is

$$\begin{aligned} \dot{I}_D &= \frac{\dot{V}_D}{V_T} I_S \exp(V_D/V_T) \\ &= \frac{\dot{V}_D}{V_T} (I_S + I_D) \quad \Rightarrow \quad \dot{V}_D = \frac{V_T}{I_S + I_D} \dot{I}_D. \end{aligned} \quad (5)$$

Substitute equation (5) into (4) and that result into (3) to get

$$I_L = \frac{CV_T}{I_S + I_D} \dot{I}_D + I_D. \quad (6)$$

Going clockwise around the loop consisting of the diode and coil in figure 1, the voltage loop rule can be rearranged as

$$V_D = -L\dot{I}_L - RI_L. \quad (7)$$

Substitute equation (7) into (2) to get

$$I_D = I_S \left[\exp\left(-\frac{L\dot{I}_L + RI_L}{V_T}\right) - 1 \right] \quad (8)$$

whose time derivative is

$$\dot{I}_D = -I_S \frac{L\dot{I}_L + RI_L}{V_T} \exp\left(-\frac{L\dot{I}_L + RI_L}{V_T}\right). \quad (9)$$

Substitute equations (8) and (9) into (6) and simplify to obtain

$$LC \ddot{I}_L + RC \dot{I}_L + I_L = I_S \left[\exp\left(-\frac{L\dot{I}_L + RI_L}{V_T}\right) - 1 \right] \quad (10)$$

which is a second-order differential equation for $I_L(t)$ in terms of circuit parameters. The inductance prevents any sudden change in current, so one initial condition at the instant the switch is flipped from position 1 to 2 is $I_L(0) = 0$. To get the other initial condition, substitute equation (7) into the first equality in (4) to get $Q = LC\dot{I}_L + RC I_L$. Now use the first initial condition and $Q_0 = C\varepsilon$ to obtain $\dot{I}_L(0) = \varepsilon/L$. Equation (10) can then be solved numerically in Mathematica (or other such software) by providing values for L , C , R , ε , I_S , and V_T . Finally $I_L(t)$ can be substituted into equation (7) to calculate $V_C = -V_D = L\dot{I}_L + RI_L$ for direct comparison with the voltage measured by the oscilloscope probe discussed in the caption of figure 1.

3. Experiment and discussion

The circuit in figure 1 is constructed out of commonly available components, so that undergraduate laboratory instructors can reproduce it. As discussed in the previous section, a 1N4148 silicon diode is used with $V_T = 51.6$ mV and $I_S = 25$ nA. That diode has been employed in many previous experiments [4, 5, 14–16]. To maximize the decay time constant of the coil, one with a large L/R ratio is selected. A good choice is a 3400 turn air-core Heath coil [17]. A Protek 506 multimeter is used to measure $L = 0.81$ H and $R = 62.7$ Ω . In accordance with equation (1), a DC power supply of large (but safe) maximum voltage (namely Tenma model 72-6615, variable from 0 to 30 V) is utilized. The same multimeter is used to accurately adjust it to $\varepsilon = 25.0$ V. Lastly it is convenient to choose the capacitance so that an easily measured oscilloscope trace of a few tenths of a second captures the circuit behavior of interest. Six unpolarized capacitors (WEST-CAP model A94W1474-3 nominally rated at 0.47 μ F and 100 V DC each) are wired in parallel to give $C = 2.96$ μ F as again measured with the same multimeter.

Begin by checking both the differential equation solver and the circuit measurement by leaving the diode out of the circuit. In equation (2) that corresponds to putting $I_S = 0$, which zeroes out the right-hand side of equation (10). The data from the oscilloscope (Keysight model DSOX2002A) is transferred as a CSV file to Mathematica running on a laptop. The results are overlaid in figure 3 and are seen to be in good agreement with each other. The slight difference between them can be attributed to uncertainty in the multimeter readings of the values of R , L , and C of the coil and capacitor, and to stray values of those three quantities in the other parts of the circuit. The red curve computed numerically from equation (10) in this figure matches the known analytical solution [2] for an undriven series RLC circuit.

Proceeding now to the circuit in figure 1 with the diode in place, the experimental data is graphed in figure 4. It shows all of the expected major features discussed in the preceding section. Namely, the curve starts at a voltage of $\varepsilon = +25$ V, and it then executes a quarter of an oscillation where the full period is $T = 2\pi(LC)^{-1/2} = 9.7$ ms (a complete cycle of which can be seen over the horizontal range from 25 to 35 ms). Next, it levels off at $-V_F = -0.7$ V while its magnitude slowly decays for about 2.8 periods in accordance with equation (1). This decay subsequently causes the diode to essentially shut back off, and the circuit resumes oscillating with underdamped RLC sinusoids thereafter.

The plateau region in the data is carefully remeasured less noisily on a vertically expanded scale and plotted as the blue curve in figure 5. For comparison, the theoretical prediction from the numerical solution of equation (10) is plotted as the red curve in that figure. There is fair agreement between the two curves. More detailed agreement can be achieved by adjusting parameters such as the diode thermal voltage and reverse saturation current, because the values adopted for them above are only approximate. However, that will not be pursued here, because the present goal is to demonstrate that the main features of the data can be successfully modeled using simple parameters that students can directly measure or look up online.

To increase the time duration of the plateau, during which a nearly constant current (useful for various applications) flows clockwise around the diode-coil loop in figure 1, a coil with a larger value of its L/R ratio is required [9]. That suggests trying a coil that is wound around an iron core [18]. A readily available choice [19, 20] is a variac, such as a Superior Electric Variable Transformer model 3PN116C. Replace the coil in figure 1 with a connection across the output of such a variac, dialed all the way up to its maximum (namely to an output voltage of 140 V for this particular transformer, but care should be taken to tape over the 120 V input plug to the transformer so that students do not try to insert it into a wallplug). The Protek 506 multimeter is

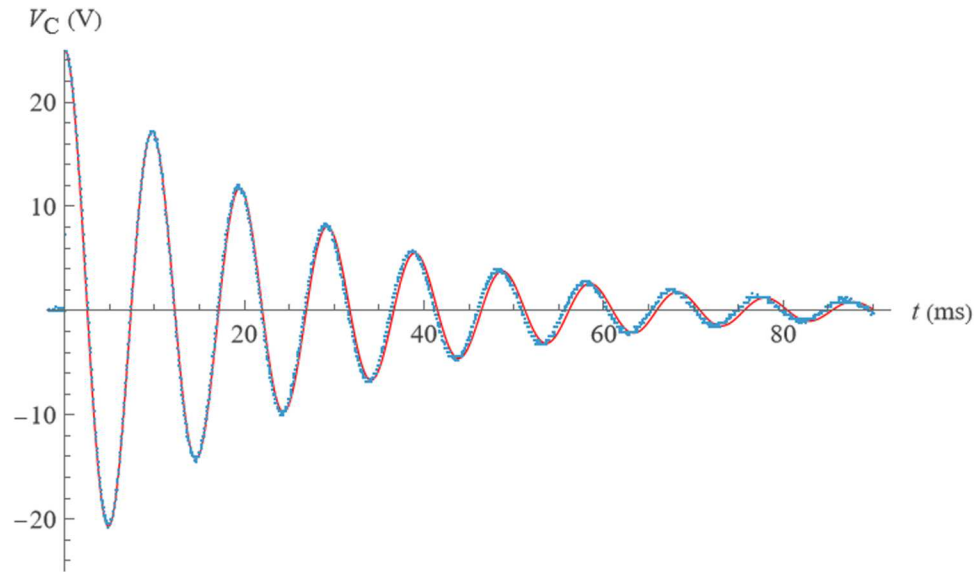


Figure 3. Damped RLC oscillations calculated theoretically (red curve) from equation (10) with $I_S = 0$, and measured experimentally (blue dots) using the circuit in figure 1 with the diode removed. The parameters are $L = 0.81$ H, $R = 62.7$ Ω , $C = 2.96$ μF , and $\varepsilon = 25.0$ V.

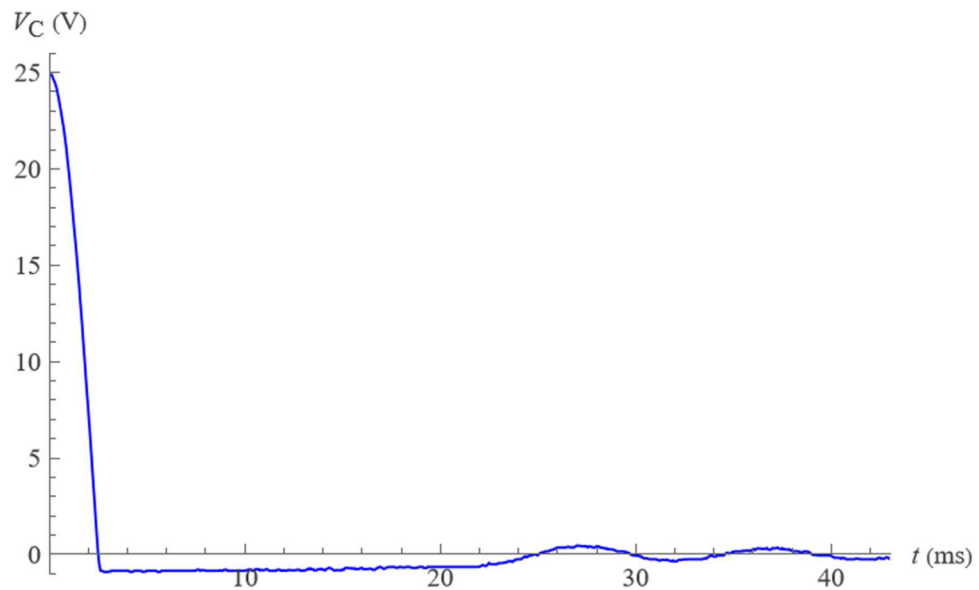
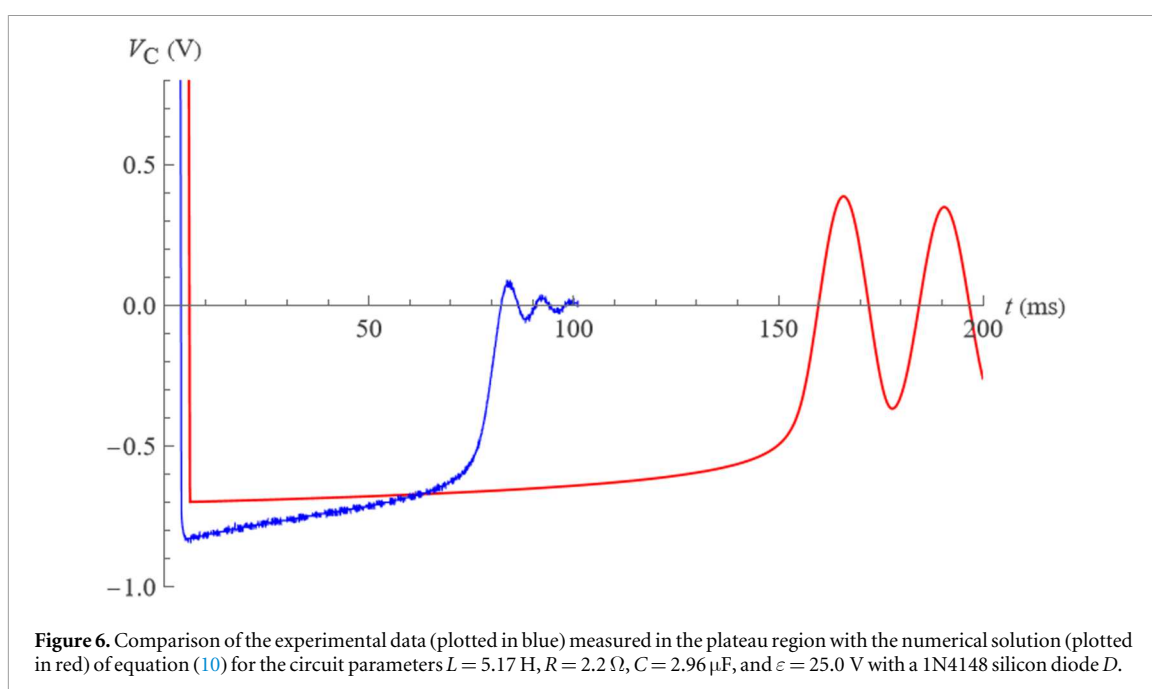
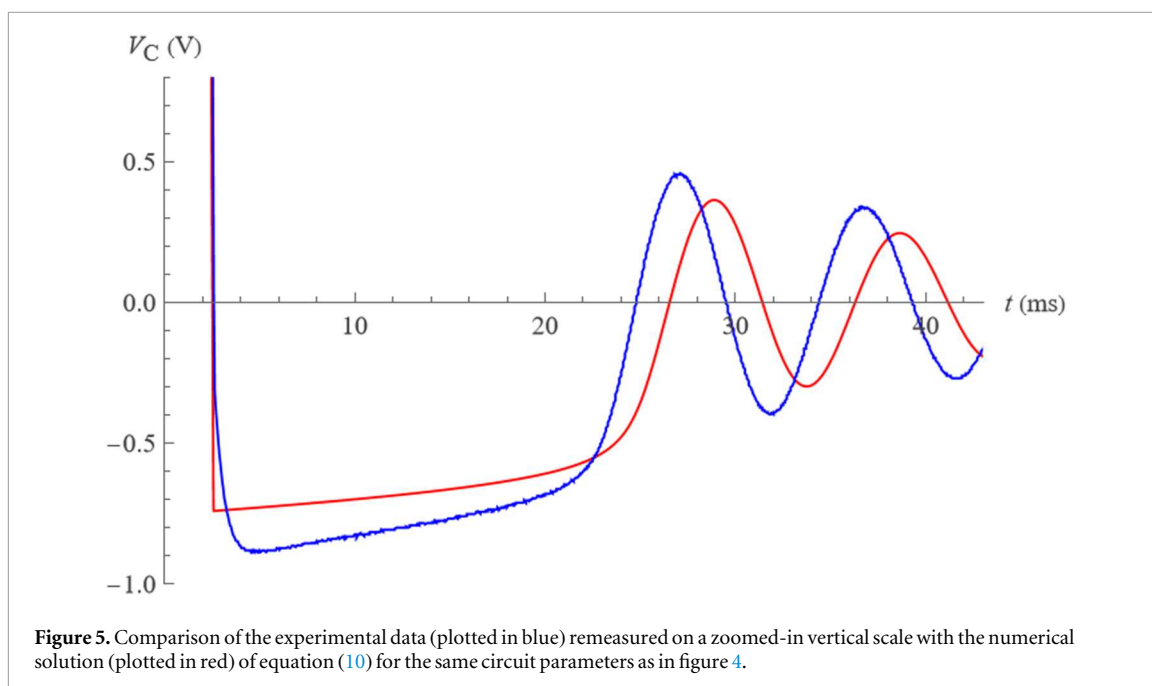


Figure 4. Single trace measured by the oscilloscope probe in figure 1 when switch S is flipped to position 2 at $t = 0$ after it has been in position 1 for a long time. The circuit parameters are $L = 0.81$ H, $R = 62.7$ Ω , $C = 2.96$ μF , and $\varepsilon = 25.0$ V with a 1N4148 silicon diode D .

used to measure its inductance as $L = 5.17$ H and its resistance as $R = 2.2$ Ω . The measured plateau is then compared to theory in figure 6. The good news is that the experimental plateau is about four times wider than what is seen in figure 5 (after accounting for the different horizontal timescales of the two graphs), but the bad news is that equation (10) predicts it should be about another factor of two wider than what is observed. The cause of the faster decay in the experimental data (explaining both the narrower plateau and the weaker post-plateau oscillations) compared to theory is that there is additional dissipation beyond the DC electrical resistance (due to both the coil R and the diode R_D). Namely, there are energy losses stemming primarily from hysteresis and to a lesser extent from eddy currents induced in the ferromagnetic core [21–23]. Modeling these additional losses is not trivial because they result in effective values of L and R of the coil that are frequency dependent [8, 24, 25]. Avoiding that is in fact the reason that this section began by using an air-core Heath coil [26].



4. Conclusion

The circuit discussed here provides a way to introduce diodes to physics students. It can be analyzed approximately using the familiar simplified model of figure 2(a) either with a zero or a positive value of V_F and ignoring the resistance of the coil. However, building and characterizing the circuit experimentally shows that it is necessary to employ the more accurate model of figure 2(b) and to include the coil's resistance in order to properly represent the major features in the data. Reasonable agreement is then found between theory and experiment for an air-core coil, using independently assumed or measured values of the circuit parameters.

Similar concepts can be employed to analyze the charging and discharging of a capacitor through a reverse-biased diode [27]. A nice feature of the latter situation is that the differential equation (for the voltage across the capacitor) is then found to be first order and analytically solvable, as opposed to the second-order equation (10) found here that is only numerically solvable. That analytic solution gives rise to a very nearly linear time dependence for the charging and discharging of the capacitor, in contrast to the usual saturating exponential when a resistor is used rather than a diode.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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