Experiment 201-4

Variable Capacitance

Introduction

In this experiment, the capacitance of a parallel plate capacitor will be determined by measuring the time that it takes the voltage on it to decay to half the initial value as it is being discharged through a known resistance. This will be done at a number of different plate separations with only air between the two plates, and also at one plate separation with a pane of glass placed between the plates. The equation relating capacitance to plate separation will be found using graphical analysis.

The time for the capacitor to loose its charge will be very short — much too short to measure with a clock as you did in Experiment 3. Instead, square wave pulses from a signal generator will charge the capacitor, and then it will completely discharge in a fraction of a second. The charging/discharging cycle will repeat continuously. As the capacitor discharges, the voltage across it will be displayed and measured on an oscilloscope screen.

Theory: Capacitance, C depends only on the surface area, A of the capacitor plates, the distance, d between them, and the permittivity, ε of the material between them. The equation relating these factors is

$$C = \varepsilon A d^n \tag{4.1}$$

where n is an integer. The permittivity of the material between the plates is given by

$$\varepsilon = K\varepsilon_0 \tag{4.2}$$

where ε_0 is the permittivity of free space and K is its dielectric constant[1].

The voltage, V across a capacitor discharges through a resistor of resistance, R according to

$$V = V_0\, \mathrm{e}^{-t/RC} \tag{4.3}$$

where V_0 is the initial voltage and t is the time.

By definition, the time required to reduce the voltage on the capacitor by half is $t_{1/2}$ (i.e., $t = t_{1/2}$ when $V = V_0/2$), so from equation (4.3) we obtain the following expression for the capacitance:

$$C = \frac{t_{1/2}}{R \ln 2} \tag{4.4}$$

Thus, if the time for the voltage across a capacitor to be reduced by half and the resistance through which it is discharging are known, the capacitance of the capacitor can be found.

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[1] K also equals the ratio of the capacitance of the capacitor with some material between the plates to the capacitance of the same capacitor with no material between the plates.

Purpose

The primary objective of this experiment is to determine the equation relating the capacitance of a parallel plate capacitor to the plate separation. This essentially means determining the values of the integer, n and εA in Equation (4.1). Two secondary objectives are: (1) to determine a value for the permittivity of air (which can essentially be considered the permittivity of free space) and (2) to determine the dielectric constant of glass.

Procedure

Before beginning this experiment, familiarize yourself with the controls of the *BK PRECISION* 4003A function generator and of the OWON PDS 5022S digital storage oscilloscope by reading the sections at the end of this experiment. In this experiment the square wave from the function generator will charge the capacitor 100 times per second. After each charge, the capacitor will quickly discharge through a resistor. The oscilloscope screen displays the voltage across the capacitor as a function of time and provides cursors to measure the half-time.

Measure the length and the width of the plates on the apparatus with a ruler and calculate their surface area, A. Set the plate separation on the variable capacitor to its minimum value and put the top plate in place. Use coaxial cables to connect the **OUTPUT** of the function generator to the capacitance apparatus and the capacitance apparatus to the **CH 1** input of the oscilloscope, to construct the circuit shown in Figure 4.1.

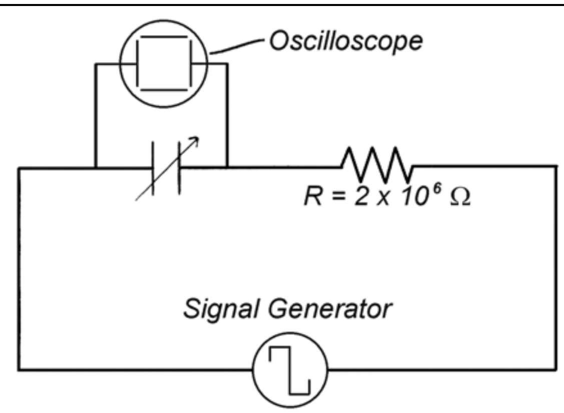

Figure 4.1 Circuit Diagram

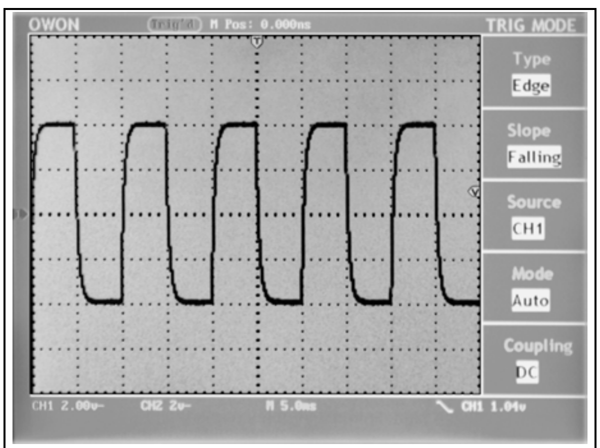

Figure 4.2 Preliminary Signal Display

Function Generator Settings: Select the 500 Hz range and a square wave signal. Set the output level to the midpoint of its range, turn on the generator and fine tune the frequency to 100 Hz.

Turn on the capacitance apparatus and the oscilloscope. The oscilloscope display will instruct you to press any key to get started.

Preliminary Set-up of the Oscilloscope:

1. Press the CH 1 menu key, then select Coupling DC, Channel ON, Probe 1X, Inverted OFF.
2. Press the TRIG menu key, then select Type Edge, Slope Falling, Source CH 1, Mode Auto, and Coupling DC.
3. Press the AUTOSET key, then adjust the trig level to 1.00 volts.

You should get a signal like the one shown in Figure 4.2. It displays the voltage across the capacitor as a function of time. You can see the square wave signal from the function generator with the charging and discharging curves at the leading and trailing edges of each pulse.

Determine $t_{1/2}$: Repeat the following procedures to get the value of $t_{1/2}$ directly from the oscilloscope display for each plate separation on the capacitance apparatus.

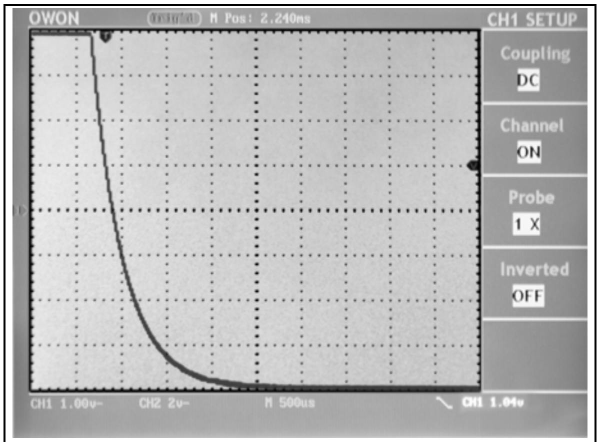

Figure 4.3 Setting the Baseline

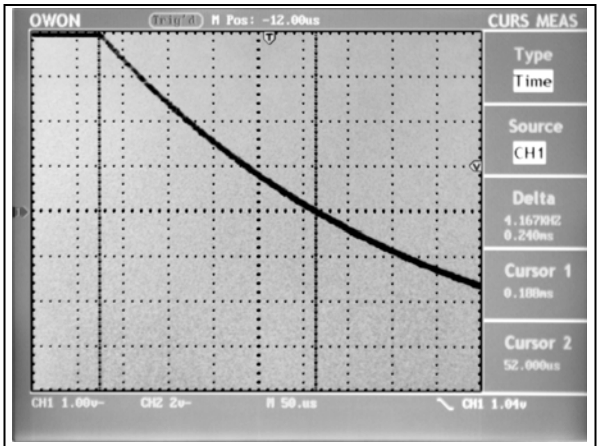

Figure 4.4 Cursor Display & Measurement

Set the **VOLTS/DIV** for **CH 1** on the oscilloscope at 2.0 volts/cm, then adjust the **OUTPUT LEVEL** control knob on the function generator to set the amplitude of the square wave at 4.0 volts. Switch the **VOLTS/DIV** to 1.0 volts/cm and adjust the vertical **POSITION** so that the baseline of the square wave rests at the bottom of the display. Expand the horizontal scale using the **SEC/DIV** knob to make sure that the baseline of the trace rests at the bottom of the display, as is illustrated in Figure 4.3. You will probably have to use the horizontal **POSITION** knob to move the decay curve so that all of it can be seen.

Expand the horizontal scale with the **SEC/DIV** knob on the oscilloscope to so that the time required for the voltage to fall to half its original value takes up at least half of the distance on the screen (i.e., at least five scale divisions). Use the horizontal **POSITION** knob to move the trace so that you can see the top of the square wave in the upper left portion of the display, as shown in Figure 4.4.

Press **RUN/STOP** to freeze the display, then press the **CURSOR** key and select Type Time. Adjust **CURSOR 1** so that it registers the very beginning of the decay curve, and **CURSOR 2** so that it intersects the decay curve half way down the display, as illustrated in Fig. 4.4. The value of $t_{1/2}$ is displayed on the right hand side of the screen under Delta in the cursor menu.

Calculate the total capacitance, C_T via Equation (4.4) and tabulate the result with the appropriate plate separation. (The resistance in the circuit is 2.0 MΩ ± 5%.)

Capacitance of the Coaxial Cable, C_C: The coaxial cable used to make connections to the apparatus has a small capacitance that must be taken into account. To do this, remove the top plate from the apparatus and place it on the desk top beside the apparatus. The only capacitance in this configuration is that due to the coaxial cable. Find this value the same way as you did above. The actual capacitance of the capacitor, is then given by

$$C = C_T - C_C . \tag{4.5}$$

Measure plate separations: First remove the top plate from the apparatus. Hold the caliper in a vertical orientation with the jaws at the top. Place the bottom of the caliper on the top of one of the pins used to hold the top plate. Extend the rod of the caliper until it touches the bottom plate, then read the vernier caliper scale. Do this for each of the four pins and average the result, then convert the average from millimeters into metres.

Finally, **place a pane of glass between the plates** of the capacitor with the top capacitor plate placed directly on top of the glass plate and determine the capacitance. Use the vernier caliper to measure the thickness of the glass plate.

Determination of n : Plot a graph of log C versus log d on log-log graph paper. The slope of this graph rounded to the nearest integer is the value of n in Equation (4.1).

Determination of εA : Now plot a graph of C versus d^n on linear paper using the integer value of n found above to tabulate the values of d^n. The slope of this graph is equal to εA. Use the above numerical values to write an equation relating C to d.

Determination of ε for air : Use the surface area of the plates along with the slope of the above graph to calculate a value of ε for air. This value can essentially be considered to be equal to the permittivity of free space, ε_o.

Dielectric constant of glass : Use the equation you have found relating C and d to calculate the capacitance for the same plate separation in air as the thickness of the pane of glass. This value divided into the capacitance found with the glass between the plates is equal to the dielectric constant, K of the glass. Find this value.

Some Points for Discussion

When resistors are connected in parallel, the reciprocals of their resistance are added to give the reciprocal of their total resistance. For capacitors in parallel, however, the total capacitance is simply the sum of the individual capacitance values. Can you explain why this is so?

Look up reference values for the permittivity of free space and for the dielectric constant of the glass. Do not forget to cite the sources of your reference values. How do your experimental values compare to the reference values?

References

1. Halliday, D., Resnick, R., & Krane, K. S., *Physics, Volume 2, 5th edition, Chapter 26, pp. 592–594 and Chapter 30, pp. 679–682*

BK PRECISION 4011A Function Generator

The *BK PRECISION* 4011A function generator generates a periodic signal in the form of a sine wave, square wave, triangular wave, etc. Only the features that are used or need to be set for this experiment are described here.

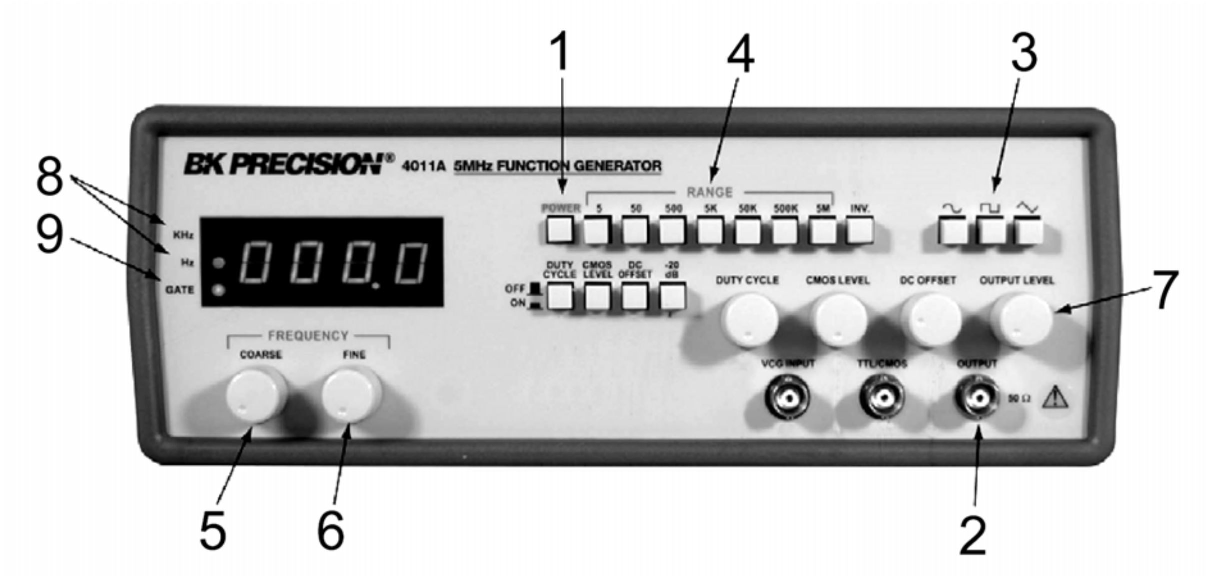

Figure 2.4 *BK PRECISION* 4011A Function Generator

1. The **POWER** switch turns the power on and off.
2. The **OUTPUT** terminal is the BNC terminal on the bottom right-hand corner of the front panel.
3. A sine (∼) wave is selected by pushing the appropriate function button.
4. The frequency **RANGE** of output frequencies is selected by this set of buttons. The button indicates the maximum frequency obtainable. The minimum frequency obtainable on the selected range is 0.1 times the maximum.
5. The **COARSE FREQUENCY** knob is located just below the display With the **RANGE** set on 500, you can adjust the output frequency continuously from 5 to 500 Hz, as read directly from the 4-digit display directly above it.
6. The **FINE FREQUENCY** knob should be set at the mid-point of its range before making the **COARSE** adjustment. It allows you to tune in the desired frequency more precisely.
7. The **OUTPUT LEVEL** knob controls the amplitude of the signal. The zero output position is fully counter clockwise, maximum is fully clockwise.
8. The **Hz** and **kHz** LEDs indicate whether the display is reading in Hz or kHz.
9. The **GATE** LED indicates when the display is updated. If the 50 kHz though 5 MHz ranges are selected, it will flash 10 times per second. It flashes once per second on the 50 Hz through 5 kHz ranges, and once every 10 seconds on the 5 Hz range.

OWON PDS5022 Digital Storage Oscilloscope

An oscilloscope is used to display electrical signals on a cathode ray tube. The vertical axis on the display represents the amplitude of the signal while the horizontal axis represents time. Only the features of the oscilloscope which are used or need to be set in this laboratory are described here.

1. The **POWER** switch.
2. The **AUTOSET** button automatically adjusts the scope display to display the signal.
3. The BNC signal inputs. You can use either **CH 1** or **CH 2**.
4. The rotating finger knob is used to adjust the brightness and contrast of the display.

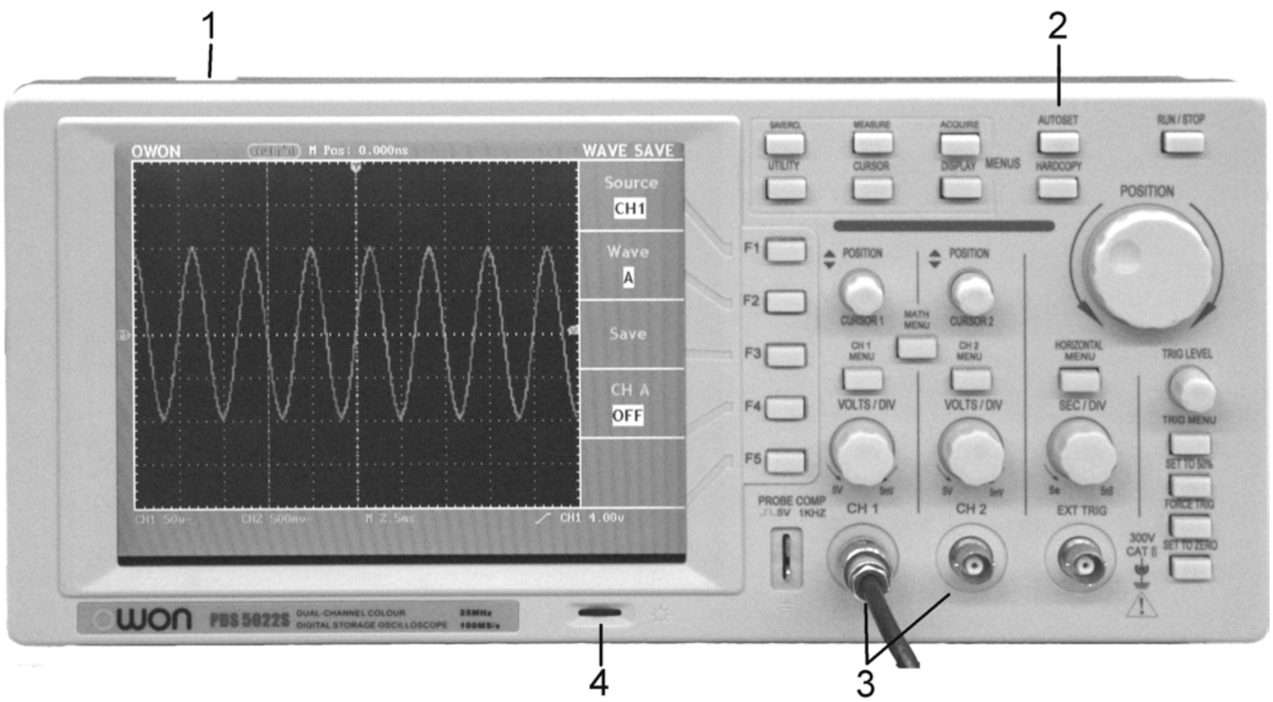

Figure 2.5 OWON PDS5022 Digital Storage Oscilloscope