

## Diode Charge Pump AM-FM Demodulators

Frequency-to-voltage converters form part of a wide variety of instrumentation circuits. They also find use in radio as FM demodulators. One interesting configuration for this application is the Diode Charge Pump circuit (DCP), which also doubles as an AM detector.

The DCP is basically a pulse-driven half-wave voltage doubler. Its use as a demodulator derives from the analysis of charge transfer taking place between circuit components.

In this article we will attempt to explain why the demodulation process takes place in the DCP. Following, the circuit will be studied under AC sine-wave excitation.

Let's begin then analysing a voltage doubler driven by a periodic train of single-polarity pulses having a duty cycle of 50% (Fig.1.a). We shall model this situation by a switch that toggles between a battery delivering  $V_1$  volts and a resistor  $R_1$  connected to ground (Fig.1.b). The switch stays in each position equal periods of time.

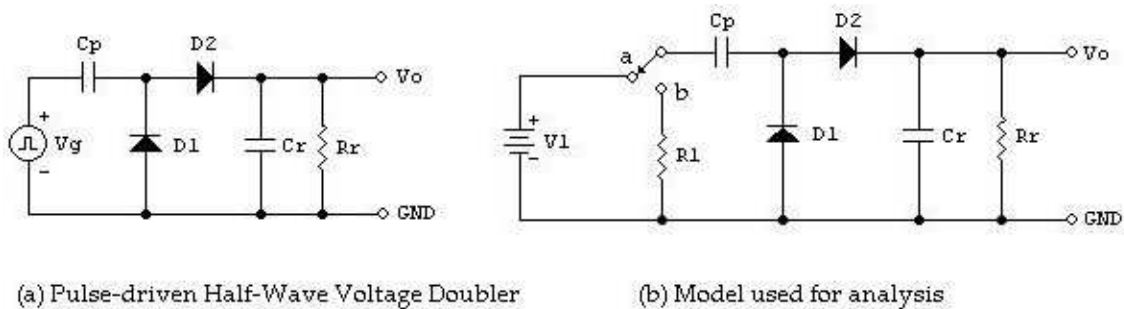


Fig.1 The Diode Charge Pump Circuit

In Fig.1.a,  $C_p$  is responsible for pumping charge towards the output capacitor  $C_r$ , which acts as a reservoir. Operation of the circuit is as follows.

When the switch is in position “a” a pulse of height  $V_1$  is applied to  $C_p$ . The charge received by this capacitor is distributed between  $C_r$  and resistor  $R_r$ . At the end of the pulse,  $C_p$  discharges through  $R_1$  and  $D_1$  (switch in position “b”). Diode  $D_2$  does not conduct (is an open circuit) on this interval. As a consequence,  $C_r$  discharges through  $R_r$ . When the switch returns to the “a” position, the operation cycle is repeated. If the pulse rate is sufficiently high,  $C_r$ 's discharge will be incomplete on each cycle and a continuous current will flow through  $R_r$ .

In the steady state, charge conservation dictates that:

$$q_1 = q_2 + q_r \quad \dots(1)$$

Here,  $q_1$  is the charge received by  $C_p$  per pulse;  $q_2$  is the charge transferred to  $C_r$ , also per pulse (it restores the charge lost by this capacitor in the preceding cycle) and  $q_r$  is the charge that diverts through  $R_r$  (fraction of  $q_1$  that doesn't reach  $C_r$ ).

The voltage across  $C_p$  increases in an amount  $\Delta V_p$  due to  $q_1$ . We may write then:

$$q_1 = C_p \Delta V_p \quad \dots(2)$$

Assuming ideal diodes (zero voltage drop when conducting):

$$\Delta V_p = V_1 - V_0$$

where  $V_0$  is the instantaneous value of the output voltage.

Substituting the above relationship into eq.(2) yields:

$$q_1 = C_p (V_1 - V_0) \quad \dots(3)$$

The voltage across  $C_r$  increases by an amount  $\Delta V_0$  due to  $q_2$ . Accordingly, we may write:

$$q_2 = C_r \Delta V_0 \quad \dots(4)$$

If we assume  $\Delta V_0 \ll V_0$ , the output voltage may be considered to be approximately constant.  $C_r$ 's discharge current in each operating cycle can then be approximated by the constant current  $i = V_0 / R_r$ . Charge  $q_2$  may be found integrating this current over one half cycle of the input signal. Thus:

$$q_2 = C_r \Delta V_0 = \int_{\frac{T}{2}}^T i \cdot dt \approx \int_{\frac{T}{2}}^T \frac{V_0}{R_r} \cdot dt$$

Working out the value for  $\Delta V_0$  yields:

$$\Delta V_0 \approx \frac{V_0 T}{2R_r C_r} \quad \dots(5)$$

and:

$$q_2 = \frac{V_0 T}{2R_r} \quad \dots(6)$$

$T$  is the repetition period of the input pulses.

For  $\Delta V_0$  to be much smaller than  $V_0$ , the following restriction must hold:

$$V_0 \gg \frac{V_0 T}{2R_r C_r}$$

or:

$$R_r C_r \gg 0.5T \quad \dots(7)$$

Being the output voltage  $V_o$  approximately constant, we may write:

$$q_r = \int_0^{\frac{T}{2}} \frac{V_o}{R_r} \cdot dt = \frac{V_o T}{2R_r} \quad \dots(8)$$

Substituting eqs. (3), (6) and (8) into eq.(1):

$$\begin{aligned} C_p(V_1 - V_o) &= \frac{V_o T}{2R_r} + \frac{V_o T}{2R_r} \\ &= \frac{V_o T}{R_r} \end{aligned}$$

Solving for  $V_o$  we obtain, with  $T = 1/f$ :

$$V_o = V_1 \frac{C_p f R_r}{C_p f R_r + 1} \quad \dots(9)$$

We must bear in mind that  $f$  is the pulse rate or number of pulses per second.

For there to exist linearity between  $V_o$  and  $f$ , it must be satisfied that:

$$C_p f R_r \ll 1$$

or that:

$$R_r C_p \ll T \quad \dots(10)$$

Under these conditions:

$$V_o \approx C_p R_r V_1 f \quad \dots(11)$$

Clearly, a linear relationship exists between  $V_o$  and the pulse rate  $f$ , and also between the output and the height  $V_1$  of the input pulses. The output linearly follows any frequency or amplitude input changes. Hence, the DCP may act as an AM/FM demodulator.

### **Sine-wave excitation analysis**

The DCP was subjected to tests with AM and FM modulated AC sine-wave inputs. In each case, successful recovery of the modulating signal could be achieved. It has then

been found advisable to analyse the demodulation process with these new input conditions.

Sine excitation suggests that it is best to look at the circuit as being a half-wave voltage doubler. With this in mind, if the source voltage  $V_g$  has an amplitude  $V_1$  and frequency  $f$ , then for the unloaded case the steady-state output voltage will be  $v_o = 2V_1$ . Note that capacitor  $C_p$  will be charged to  $V_1$  volts (Fig.2.a).

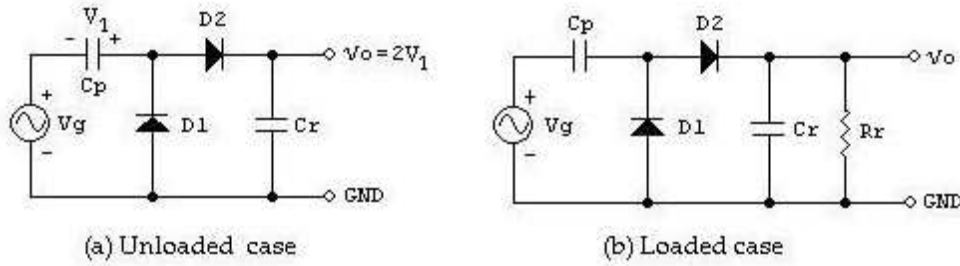


Fig.2 Half-Wave Voltage Doubler with sine input of amplitude  $V_1$  and frequency  $f$ .

Upon connection of a resistive load  $R_r$  (Fig.2.b), the output voltage  $v_o$  will no longer be a pure DC value. It will consist of a DC component  $V_o$  and some ripple superimposed on it.  $D_2$  will conduct for a brief time in the neighborhood of the positive peaks of  $V_g$ , transferring charge from  $C_p$  to  $C_r$ . This last capacitor discharges across  $R_r$  when  $D_2$  is off, which occurs during most of the time interval between positive peaks of the input voltage.  $C_p$  replenishes its charge when  $D_1$  briefly conducts in the neighborhood of the negative peaks of  $V_g$ . As a result of these actions  $v_o$  will have some ripple added, as stated before, and also will the voltage across  $C_p$ .

Let  $\Delta V_o$  be the peak-to-peak value of the ripple superimposed on  $V_o$ , and  $\Delta V_p$  that of the ripple component across  $C_p$ . If  $\Delta V_o \ll V_o$ , then:

$$\Delta V_o \approx \frac{V_o T}{R_r C_r} \quad \dots(12)$$

Charge conservation throughout one cycle of the input signal dictates now that:

$$C_p \Delta V_p = C_r \Delta V_o$$

Thus:

$$\Delta V_p = \frac{C_r}{C_p} \Delta V_o$$

$V_o$  will be given by the expression:

$$\begin{aligned}
 V_o &= 2V_1 - \Delta V_p - \frac{\Delta V_o}{2} \\
 &= 2V_1 - \frac{C_r}{C_p} \Delta V_o - \frac{\Delta V_o}{2} \\
 &= 2V_1 - \left( \frac{C_r}{C_p} + \frac{1}{2} \right) \Delta V_o \\
 &= 2V_1 - \left( \frac{C_r}{C_p} + 0.5 \right) \frac{V_o T}{R_r C_r}
 \end{aligned}$$

Solving for  $V_o$  yields:

$$V_o = \frac{2V_1}{1 + \left( \frac{C_r}{C_p} + 0.5 \right) \cdot \frac{1}{fR_r C_r}} \quad \dots(13)$$

If we let that:

$$\left( \frac{C_r}{C_p} + 0.5 \right) \cdot \frac{1}{fR_r C_r} \gg 1 \quad \dots(14)$$

then:

$$V_o \approx \frac{2V_1 f R_r C_r}{\left( \frac{C_r}{C_p} + 0.5 \right)} \quad \dots(15)$$

which is the linear relationship we are looking for. Then, for an FM signal:

$$\Delta V_{o, fm} = \frac{2V_1 R_r C_r}{\left( \frac{C_r}{C_p} + 0.5 \right)} \cdot \Delta f \quad \dots(16)$$

where  $\Delta V_{o, fm}$  represents the output voltage variations following frequency changes  $\Delta f$  of the input.

For an AM signal:

$$\Delta V_{0am} = \frac{2fR_r C_r}{\left(\frac{C_r}{C_p} + 0.5\right)} \cdot \Delta V_1 \quad \dots(17)$$

Here,  $\Delta V_{0am}$  represents the output voltage variations following amplitude changes  $\Delta V_1$  of the input signal. Thus, the output linearly follows the modulating signal.

It is desirable that the ripple at the unmodulated input frequency be much smaller than the DC output. Then, the following must also be satisfied:

$$\frac{V_0 T}{R_r C_r} \ll V_0$$

or:

$$fR_r C_r \gg 1 \quad \dots(18)$$

Summarizing:

$$1 \ll fR_r C_r \ll \left(\frac{C_r}{C_p} + 0.5\right)$$

Calculations have assumed ideal diodes, so corrections are needed to compensate for real world-diode voltage drops. For the no-modulation and FM cases,  $2V_1 - 2V_D$  may be substituted for  $2V_1$ , where  $V_D$  is the peak-voltage drop in diodes  $D_1$  and  $D_2$  (assumed equal). Higher carrier amplitudes should help overcoming these voltage drops. However, provisions should be made to protect diodes from excessive peak currents.

### **Conducted measurements**

The circuit depicted in Fig.3 was used for the FM demodulation tests. With the selected values for  $C_p$ ,  $C_r$  and  $R_r$ , the following figures were obtained:

$$\left(\frac{C_r}{C_p} + 0.5\right) \cdot \frac{1}{fR_r C_r} = 7.79$$

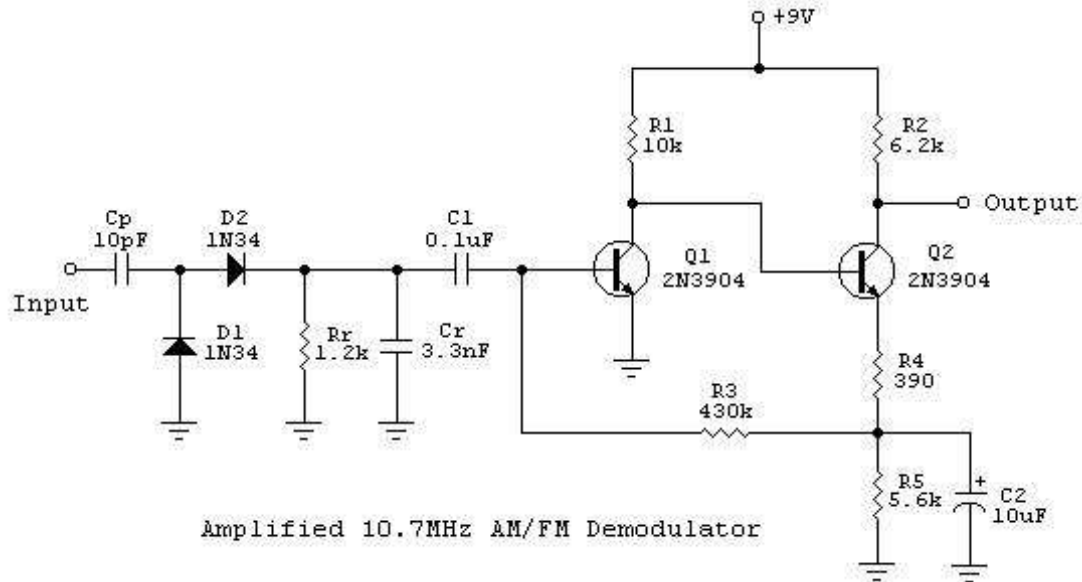
(regretfully, not much greater than 1) and:

$$fR_r C_r = 42.37$$

A Hewlett-Packard 8601A Sweeper Generator was used as the signal source for a 1-Volt amplitude 10.7MHz carrier, and accordingly, the following values were obtained at the input of the two-transistor amplifier stage:

- No modulation:  $V_o = 100\text{mV DC}$
- FM modulated carrier with  $\Delta f = \pm 75\text{kHz}$  (calibration not checked) at a 1kHz rate:  $\Delta V_{\text{ofm}} = 0.4\text{mV peak}$
- AM modulated carrier at 30% with 1kHz,  $\Delta V_1 = 0.3\text{V peak}$ :  $\Delta V_{\text{oam}} = 40\text{mV peak}$

Amplification was used in the FM case for easy viewing of the recovered modulation.



For FM detection input is a 1V-peak 10.7MHz FM carrier. Demodulated output is about 1V peak.

AM demodulation will need less post-detection amplification.

Q1's input resistance is around 5k ohms, and won't load noticeably the demodulator stage.

Voltage gain from base of Q1 to output is around 2000.

Fig.3 Circuit used for testing FM demodulation with the DCP

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