

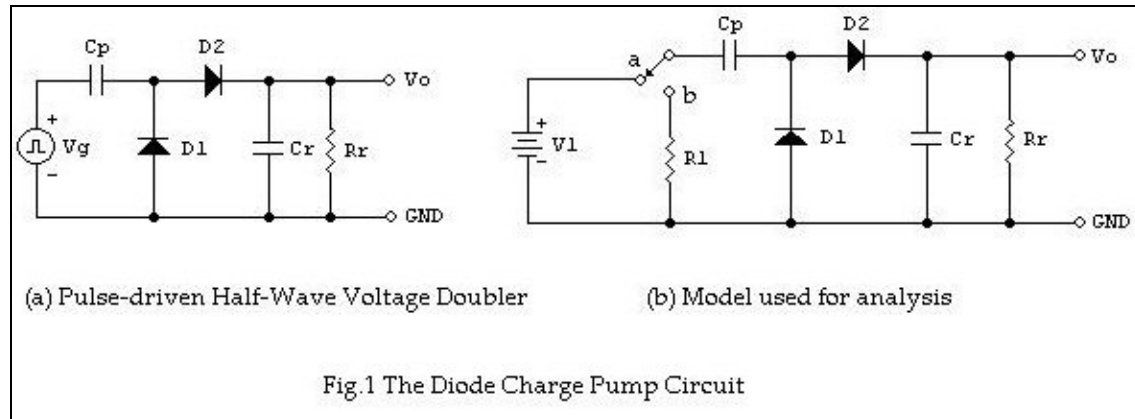
Diode Charge Pump AM-FM Demodulators

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.



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 ΔV_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 ΔV_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 ΔV_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 ΔV_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:

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

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:

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

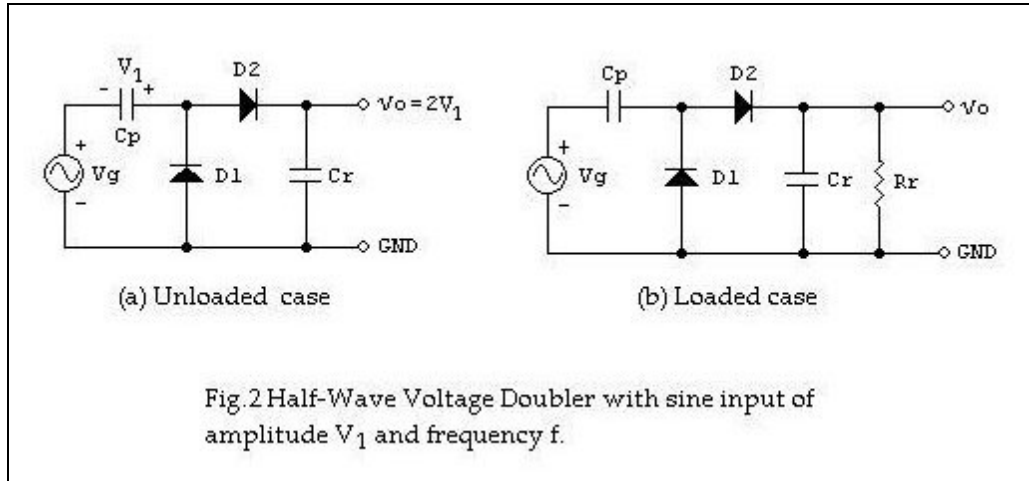
Clearly, a linear relationship exists between V_o and the pulse rate f , and also between the output and the height V_1 of the input pulses. The output linearly follows any frequency or amplitude input changes. Hence, the DCP may act as an AM/FM demodulator.

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).



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 neighbourhood 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 neighbourhood 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 ΔV_o be the peak-to-peak value of the ripple superimposed on V_o , and ΔV_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 Δf of the input.

For an AM signal:

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

Here, ΔV_{0am} represents the output voltage variations following amplitude changes ΔV_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:

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

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.

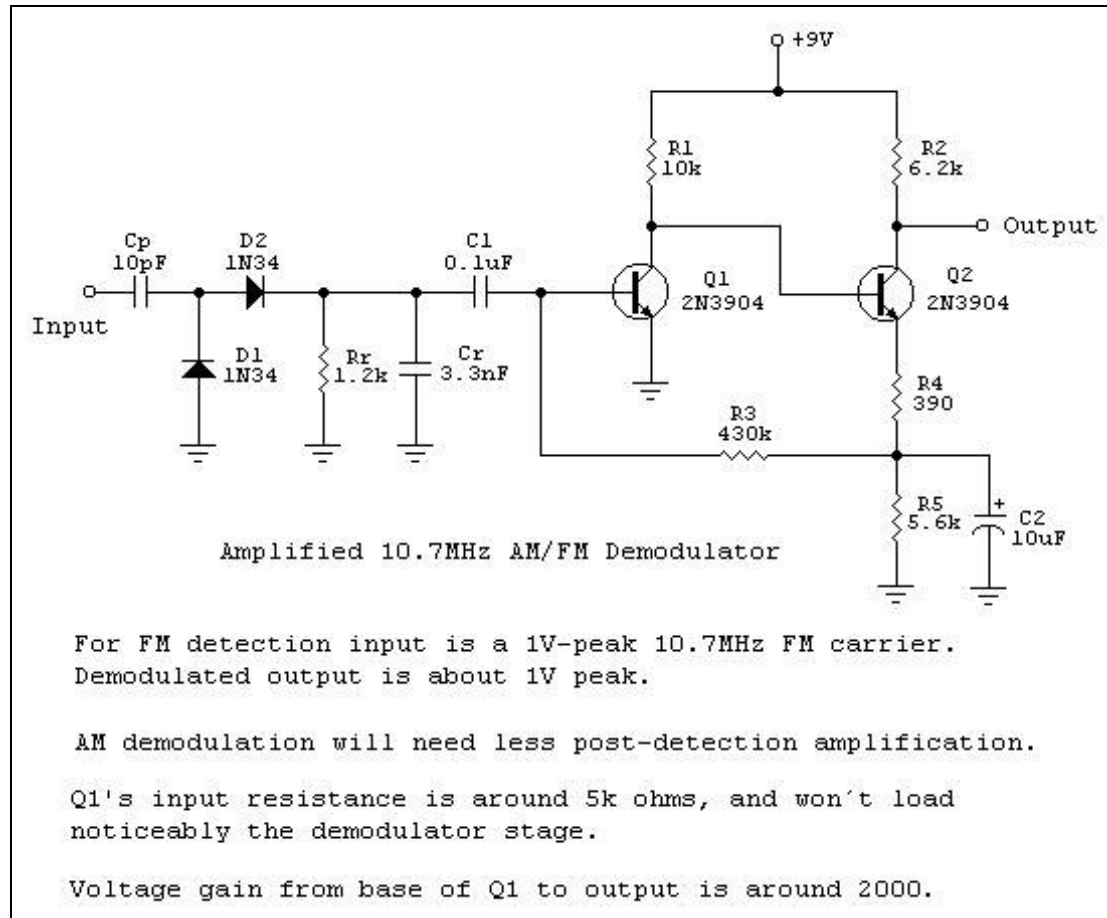


Fig.3 Circuit used for testing FM demodulation with the DCP

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