

# DC Controlled Low-Pass Filter

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## ABSTRACT

This application report describes a dc controlled low-pass filter circuit using LM3046. The cut off frequency can be varied by varying the capacitance of the low-pass filter.

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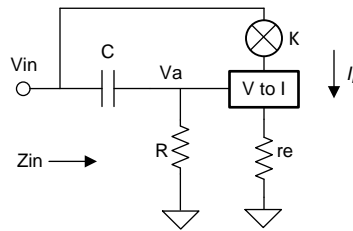
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## 1 Introduction

In medical ultrasound systems, in the CW Doppler mode the received echoes are passed through the CW mixer of the receive AFEs to demodulate the Doppler frequencies and produce I and Q signals. Output of all the AFEs are summed, filtered and amplified before digitizing. The filter requires variable cut off based on the analog signal bandwidth. The filter cut off frequencies can be selected by using a DC controlled variable capacitance circuit. By using this method continuously variable cut off frequencies can be achieved over a large range of frequency and this circuit has large signal handling capability. This can also be used as front end for precision ADCs as anti-aliasing filter and any general purpose low-pass filter.

## 2 Basic Theory



**Figure 1. DC Controlled Low-Pass Filter**

In a differentiator, output voltage leads the input voltage by  $90^\circ$ , so  $V_a$  leads  $V_{IN}$  by  $90^\circ$ . Therefore,  $I_{IN}$  leads  $V_{IN}$  by  $90^\circ$  that is the known property of a capacitor. By varying the phase shifted current, it is possible to vary the capacitance of the circuit. Current can be controlled by a DC control voltage (multiplier  $K$ ).

As shown in [Figure 1](#),  $V_a$  is the output voltage of the differentiator. The equation for  $V_a$  is shown in [Equation 1](#).

$$V_a = V_{IN} \times R / \left( R + \frac{1}{SC} \right) \quad (1)$$

For a high-pass filter,  $X_c \gg R$ ,  $R$  can be neglected in the denominator and then [Equation 1](#) becomes the following:

$$V_a = V_{IN} \times S \times C \times R \quad (2)$$

In [Figure 1](#), the current  $I_{in}$  is shown as follows:

$$I_{IN} = K \times V_a / re \quad (3)$$

By substituting  $V_a$  from [Equation 2](#) into [Equation 3](#), [Equation 3](#) then becomes as follows:

$$I_{IN} = V_{IN} \times SC \times R \times \frac{K}{re} \quad (4)$$

In [Figure 1](#), the impedance  $Z_{in}$  is shown as follows:

$$Z_{IN} = V_{IN} / I_{IN} \quad (5)$$

where

By substituting  $Z_{IN}$  in [Equation 4](#) becomes the following:

$$Z_{IN} = 1 / s((C \times R \times K) / re) \quad (6)$$

Therefore,  $Z_{IN}$  is a capacitor of the value  $C \times R \times K/re$ :

$$C_{eff} = C \times R \times \frac{K}{re} \quad (7)$$

and the circuit is capacitive.

By substituting the information from [Equation 7](#) in the equation of the cut off frequency ( $f_c = 1/(2 \times 3.14 \times R \times C)$ ), the equation becomes [Equation 8](#).

$$f_c = \frac{1}{2} \times 3.14 \times R1 \times C_{eff} \quad (8)$$

For  $C_{eff}$ ,  $re$ ,  $C$ ,  $R$ ,  $R1$ , see [Figure 2](#). By substituting [Equation 7](#) into [Equation 8](#), [Equation 8](#) becomes as follows:

$$f_c = 1 / \left( 2 \times \pi \times R1 \times C \times R \times \frac{K}{re} \right) \quad (9)$$

Hence, because of the differences in the value of 'K', the cut off frequencies of the filter can be varied.

### 3 Schematic Diagram

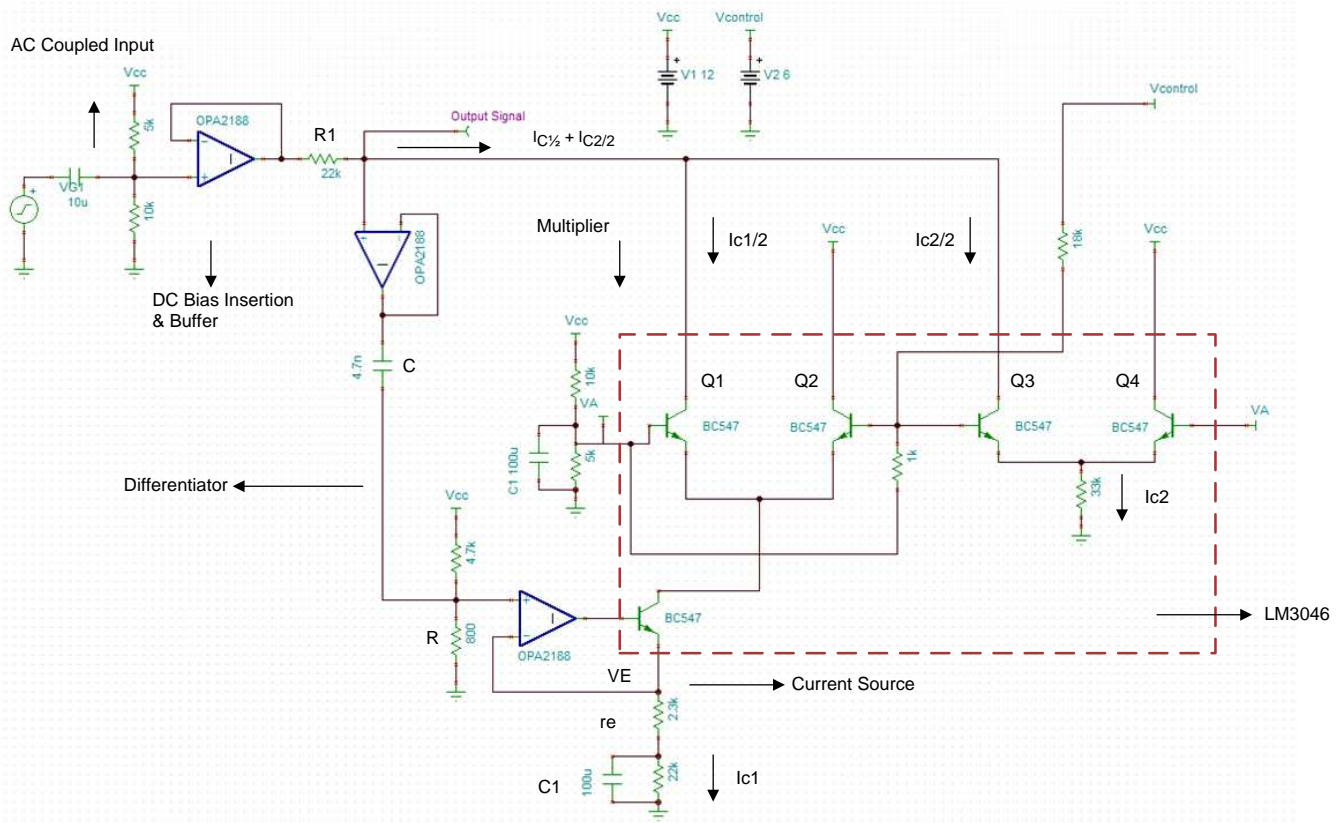


Figure 2. DC Controlled Low-Pass Filter Schematic

### 4 Schematic Description

The variable capacitance circuit is implemented using an analog multiplier that uses four transistors, which are used to make the dc conditions stable. This circuit can be integrated into a single LM3046 IC as shown in Figure 2. Differentiator output drives the current source and the multiplier factor, K is varied by the dc control voltage.

#### 4.1 DC Conditions

$$I_{c1} = \frac{V_a}{33k} = \frac{3V}{33K} = 0.1mA \tag{10}$$

For dc, C1 is open, therefore,

$$I_{c2} = \frac{V_e}{24.3K} = \frac{1.74V}{24.3K} = 0.07mA \tag{11}$$

$$V_{22K} = 22K \times (I_{c1}/2 + I_{c2}/2) \tag{12}$$

By substituting  $I_{c1}$  and  $I_{c2}$  in Equation 10 and Equation 11 into Equation 12, the equation becomes Equation 13.

$$V_{22K} = 22K \times \left( \frac{0.1}{2} + \frac{0.07}{2} \right) mA = 1.87V \tag{13}$$

So, the dc operating voltage,  $V_{dc} = 8V - 1.87V = 6.13V$ , 8V is set by the DC bias insertion, see Figure 2.

As  $V_{\text{control}}$  increases, the current through Q2 increases, therefore, the current through Q1 is reduced. As current through Q1 is reduced, the current through Q3 increases. which in turn makes the dc operating voltage constant at 6.13 V. By the four transistor configuration dc, the bias point is kept stable.

## 4.2 AC Conditions

For AC conditions, C1 is short and the emitter resistor is  $r_e$ . In ac conditions, Q3 and Q2 do not come into play. As  $V_{\text{control}}$  increases, Q2 becomes more conductive and the current through Q1 is reduced. This reduces the  $C_{\text{eff}}$  value; finally, Q1 stops conducting and the capacitance value becomes zero. For more information, see [Figure 2](#) for  $Q_1$ ,  $Q_2$ ,  $Q_3$ ,  $Q_4$ ,  $I_{C1}$ ,  $I_{C2}$ .

## 4.3 Example

$$R = 800 \Omega$$

$$C = 4.7 \text{ nF, for } K = 1$$

$$C_{\text{eff}} = (4.7 \text{ nF} \times 800 \Omega \times 1) / 2.3K \\ = 1.63 \text{ nF}$$

$$\text{Provided } f \ll f_{\text{cutoff\_differentiator}}$$

$$\text{And, } R1 = 22K$$

$$f_c = \frac{1}{2} \times 3.14 \times R1 \times C_{\text{eff}} \tag{14}$$

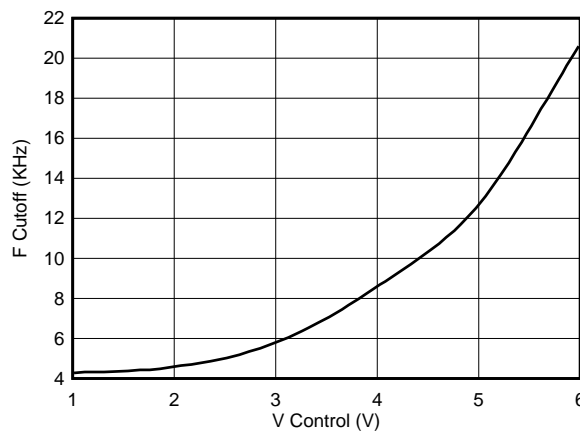
By substituting  $C_{\text{eff}}$  and R1 in [Equation 14](#) becomes  $f_c = 4.46 \text{ KHz}$  for  $K = 1$ .

$$f_{\text{cutoff\_differentiator}} = 1/2 \times \pi \times R \times C = 1/2 \times 3.14 \times 800 \times 4.7 \text{ nF} = 42.5 \text{ KHz}$$

The cut off frequency is higher than the range of the filter suggested. Therefore, by varying the dc control voltage in this example from 1 V to 6 V, the  $f_c$  can be varied from 4.4 KHz to 21 KHz.

## 5 Test Results

The circuit is tested using 1 Vpp sine wave source and the results are as shown in [Figure 3](#).



**Figure 3. Plot of Cut Off Frequencies vs Control Voltage**

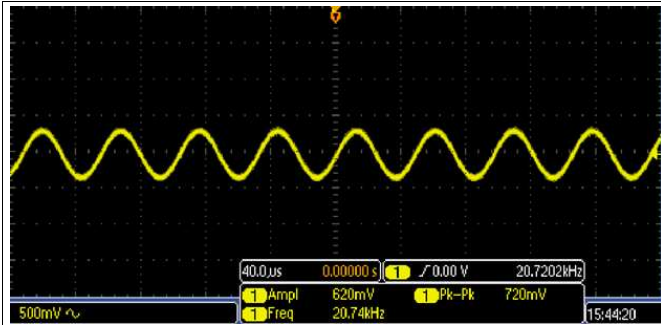


Figure 4. With  $V_{\text{control}} = 6 \text{ V}$ ,  $F_c = 20.7 \text{ KHz}$

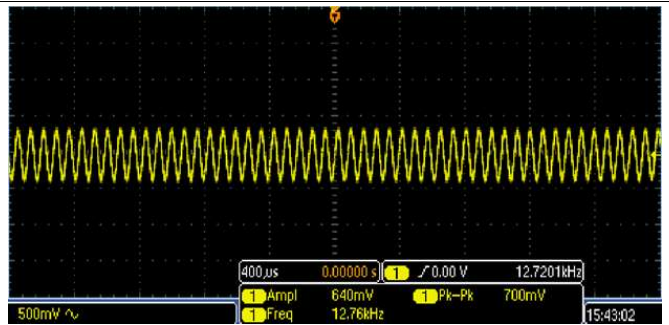


Figure 5. With  $V_{\text{control}} = 5 \text{ V}$ ,  $F_c = 12.7 \text{ KHz}$

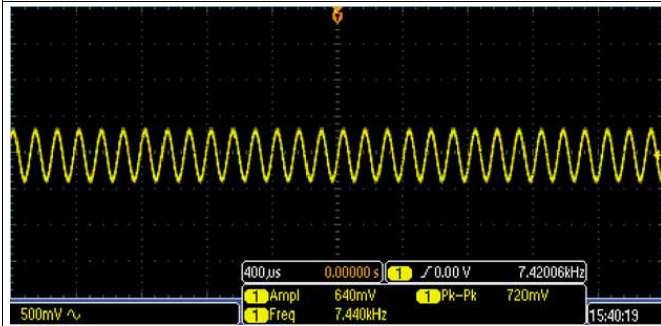


Figure 6. With  $V_{\text{control}} = 4 \text{ V}$ ,  $F_c = 7.42 \text{ KHz}$

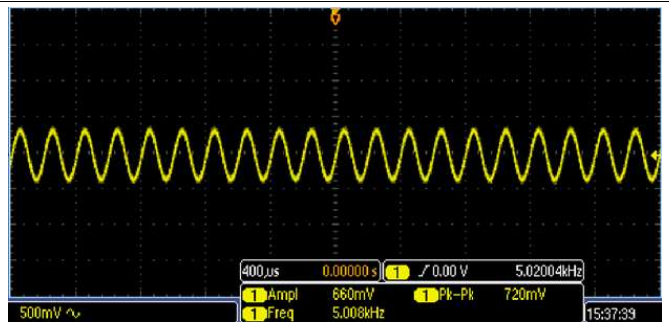


Figure 7. With  $V_{\text{control}} = 3 \text{ V}$ ,  $F_c = 5.88 \text{ KHz}$

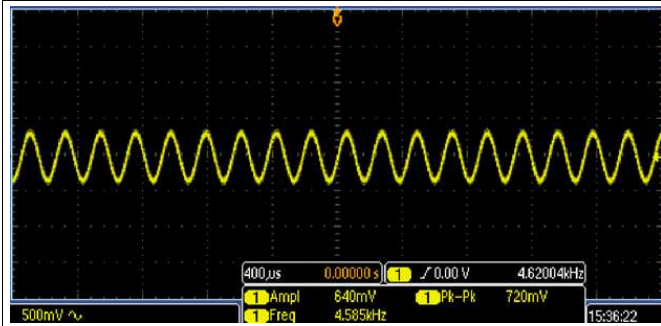


Figure 8. With  $V_{\text{control}} = 2 \text{ V}$ ,  $F_c = 4.6 \text{ KHz}$

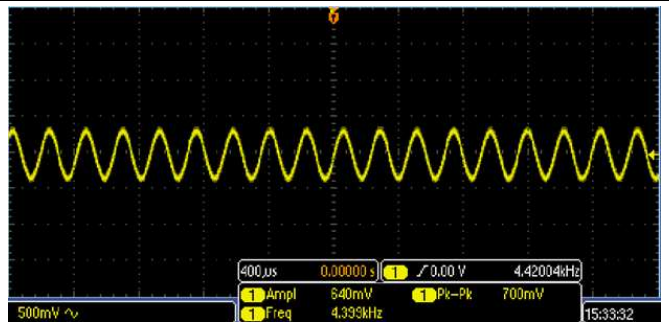


Figure 9. With  $V_{\text{control}} = 1 \text{ V}$ ,  $F_c = 4.39 \text{ KHz}$

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