

# ELEC1011 Communications and Control

## (2/11) Carrier Modulation Schemes

## Baseband vs carrier modulation schemes (CEP 1.5.3.2)

- Some of the components in baseband signals have frequencies that approach 0 Hz. e.g. some components of audio signals have frequencies as low as 20 Hz.
- In carrier modulation schemes, a baseband signal is relocated to a band of much higher frequencies by modulating it on to a sinusoidal carrier, having a high frequency  $f_c$ .
- Advantages of carrier modulation schemes:
  - Frequency Division Multiplexing (FDM) allows different signals to be modulated into different bands of frequencies without interfering with each other.
  - More channels can be accommodated at high frequencies because the bandwidth of each successive radio band (HF, VHF, UHF, etc) is ten times larger than the last.
  - Radio frequencies (3 kHz to 300 GHz) are necessary for electromagnetic waves to propagate (different frequencies have different propagation characteristics). Higher frequencies allow smaller antennas to be used. Visible frequencies (e.g. 231 THz) are necessary for optical communications schemes.

## Carrier wave parameters (CEP 2.3.2)

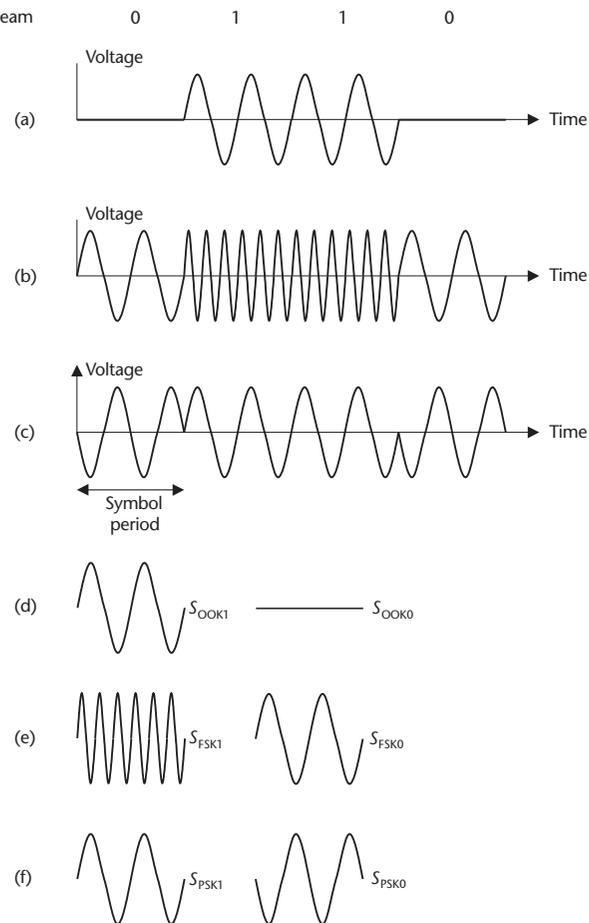
$$v_c(t) = A \cos(2\pi f_c t + \phi)$$

- **Amplitude**  $A$
- **Frequency**  $f_c$  in cycles per second (Hz)
  - **Angular frequency**  $\omega_c = 2\pi f_c$  in radians per second
  - **Period**  $T = 1/f_c$  in seconds (s)
  - **Wavelength**  $\lambda = c/f_c$  in metres (m), where the speed of light in a vacuum is  $c = 3 \times 10^8 \text{ ms}^{-1}$
- **Phase**  $\phi$

Analogue and digital message signals can be used to vary (**modulate**) one or more of these parameters.

## Digital carrier modulation - Binary shift keying

Figure 1.30



Taken from *Communication Engineering Principles*, © Ifiok Otung, published 2001 by Palgrave

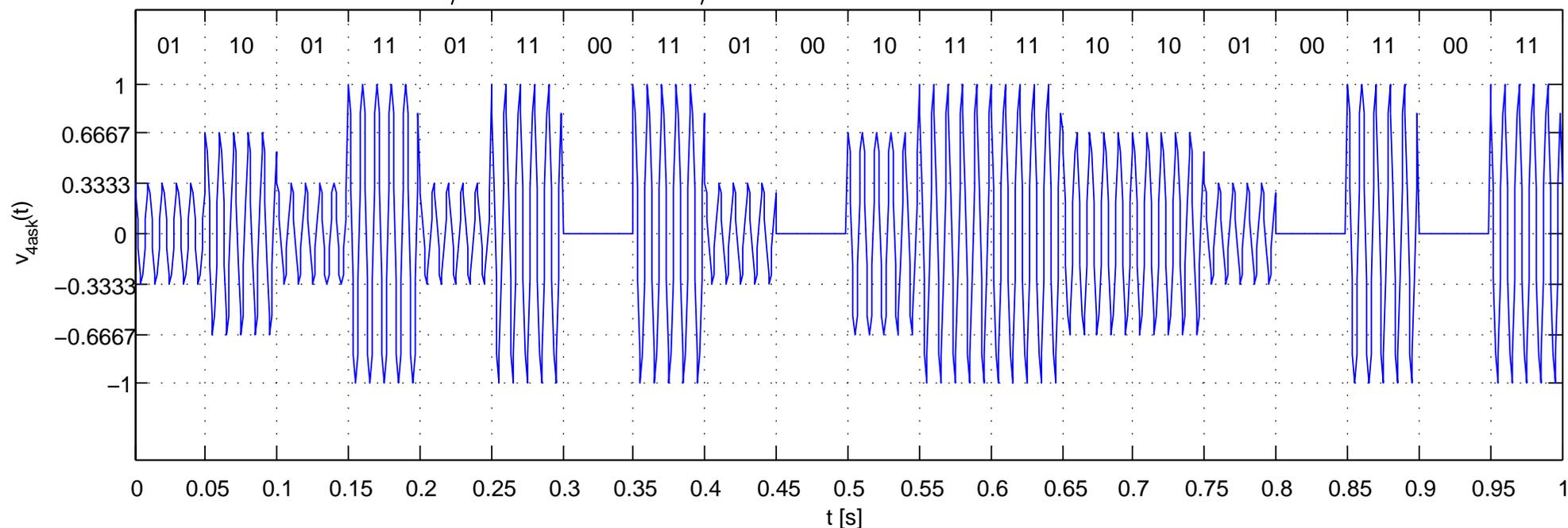
- (a) and (d) **On-Off Keying (OOK)** is a special case of **Binary Amplitude Shift Keying (BASK)**, in which different carrier amplitudes  $A$  are used for the duration of each symbol period depending on the corresponding bit value.
- (b) and (e) **Binary Frequency Shift Keying (BFSK)** uses different carrier frequencies  $f_c$  depending on the bit values.
- (c) and (f) **Binary Phase Shift Keying (BPSK)** uses values of  $0$  and  $\pi$  radians for the phase of the carrier  $\phi$  depending on the bit values.

## Digital carrier modulation - $M$ -ary shift keying (CEP 7.9)

- Binary shift keying uses  $k = 1$  bit per symbol and  $M = 2$  values for the modulated parameter of the carrier.
- In general, we can use any integer number  $k$  of bits per symbol. We just need a modulation scheme that uses  $M = 2^k$  values for the modulated parameter of the carrier. i.e.  $M$  number of amplitudes, phases or frequencies.
- The **symbol rate**  $R_s$  is  $k$  times slower than the **bit rate**  $R_b$ , i.e.  $R_s = R_b/k$ .
- More on this in Lecture 5.

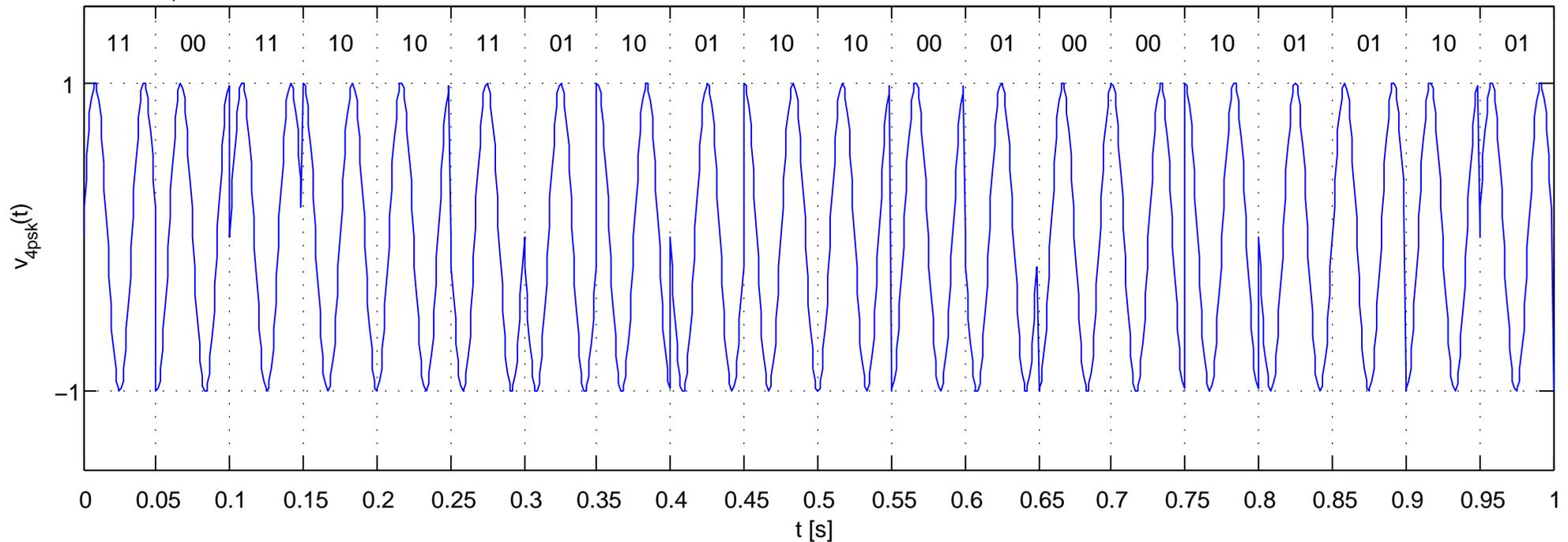
## Digital carrier modulation - 4-ary ASK (CEP 7.9.2)

- $M$ -ary ASK can use values of  $\{m/(M-1)\}_{m=0}^{M-1}$  for the amplitude of the carrier  $A$ .
- Similar to in quantization, we need a mapping between sequences of  $k$  bits and the  $M$  values of the modulated parameter of the carrier. e.g. in  $M = 4$ -ary ASK we may have  $00 \rightarrow 0$  V,  $01 \rightarrow 1/3$  V,  $10 \rightarrow 2/3$  V and  $11 \rightarrow 1$  V.



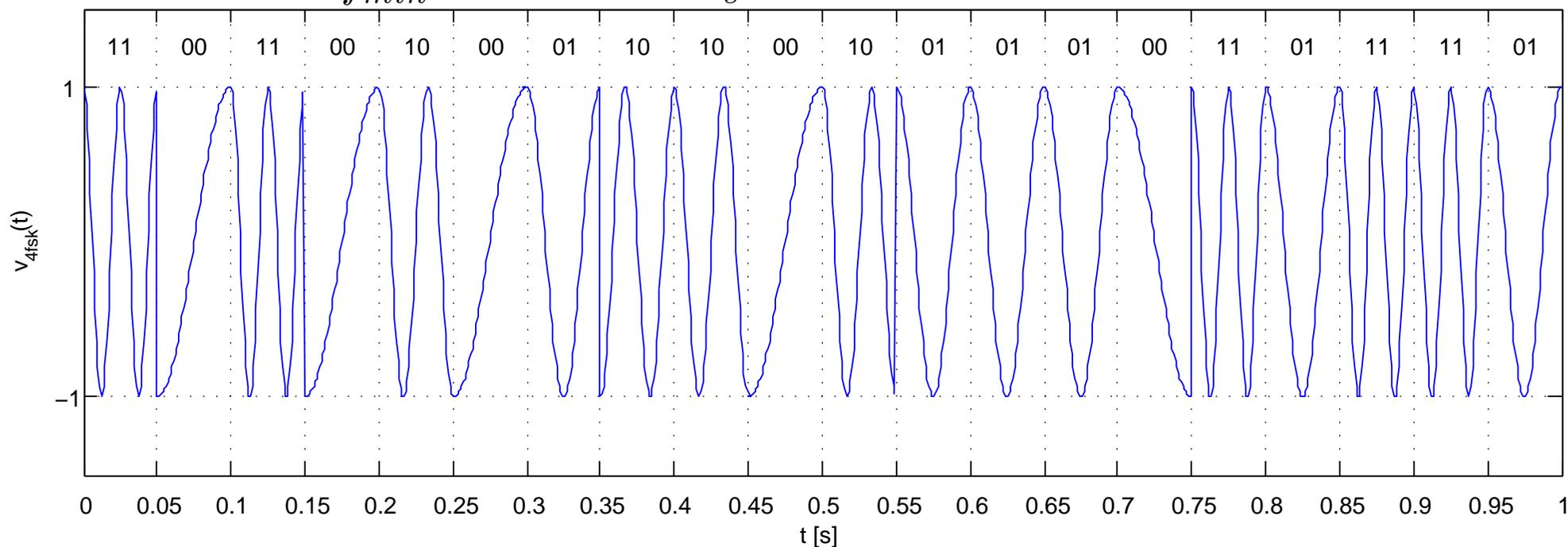
## Digital carrier modulation - 4-ary PSK (CEP 7.9.3)

- $M$ -ary PSK uses values of  $\{2\pi m/(M-1)\}_{m=0}^{M-1}$  for the phase of the carrier  $\phi$ .
- $M = 4$ -ary PSK may use 00  $\rightarrow$  0 radians, 01  $\rightarrow \pi/2$  radians, 10  $\rightarrow \pi$  radians and 11  $\rightarrow 3\pi/2$  radians.



## Digital carrier modulation - 4-ary FSK (CEP 7.9.4)

- $M$ -ary FSK uses values of  $\{f_{min} + 0.5R_s m / (M - 1)\}_{m=0}^{M-1}$  for the frequency of the carrier  $f_c$ , where  $R_s$  is the symbol rate.
- $M = 4$ -ary FSK may use 00  $\rightarrow$  10 Hz, 01  $\rightarrow$  20 Hz, 10  $\rightarrow$  30 Hz and 11  $\rightarrow$  40 Hz, in the case where  $f_{min} = 10$  Hz and  $R_s = 20$  Hz.



## Analogue carrier modulation (CEP 4.3)

- Phase modulation

$$v_{pm}(t) = V_c \cos(2\pi f_c t + k_{pm} \cdot v_m(t))$$

- Frequency modulation

$$v_{fm}(t) = V_c \cos(2\pi [f_c + k_{fm} \cdot v_m(t)]t)$$

- These are parameterized by the modulation sensitivities  $k_{pm}$  and  $k_{fm}$ .

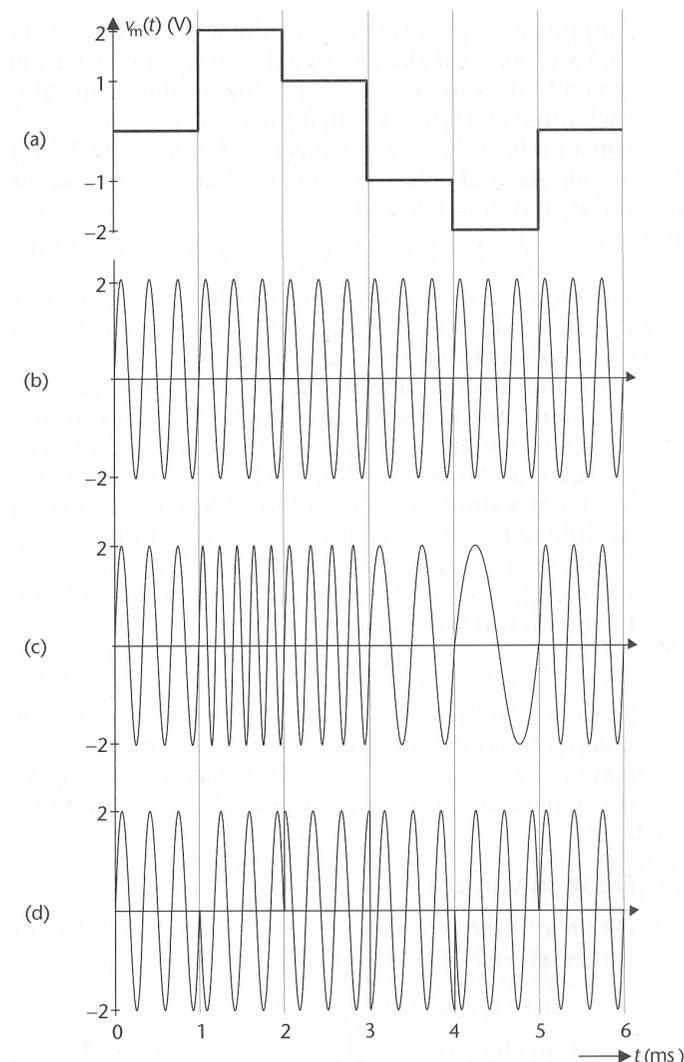
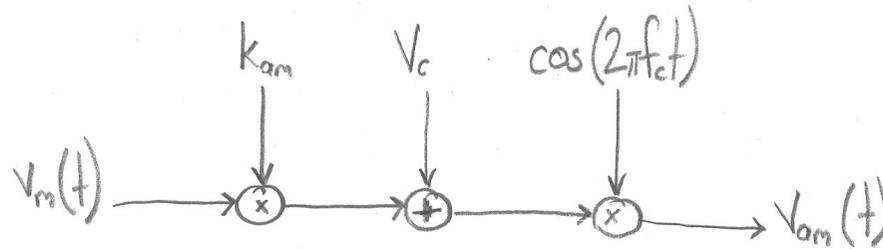


Figure 4.8 (a) Staircase-modulating signal; (b) carrier; (c) frequency modulated carrier; (d) phase-modulated carrier.

# Analogue carrier modulation - amplitude modulation (CEP 3.2)

$$v_{am}(t) = (V_c + k_{am} \cdot v_m(t)) \cos(2\pi f_c t)$$



Parameterized by:

- DC offset  $V_c$
- Modulation sensitivity  $k_{am}$

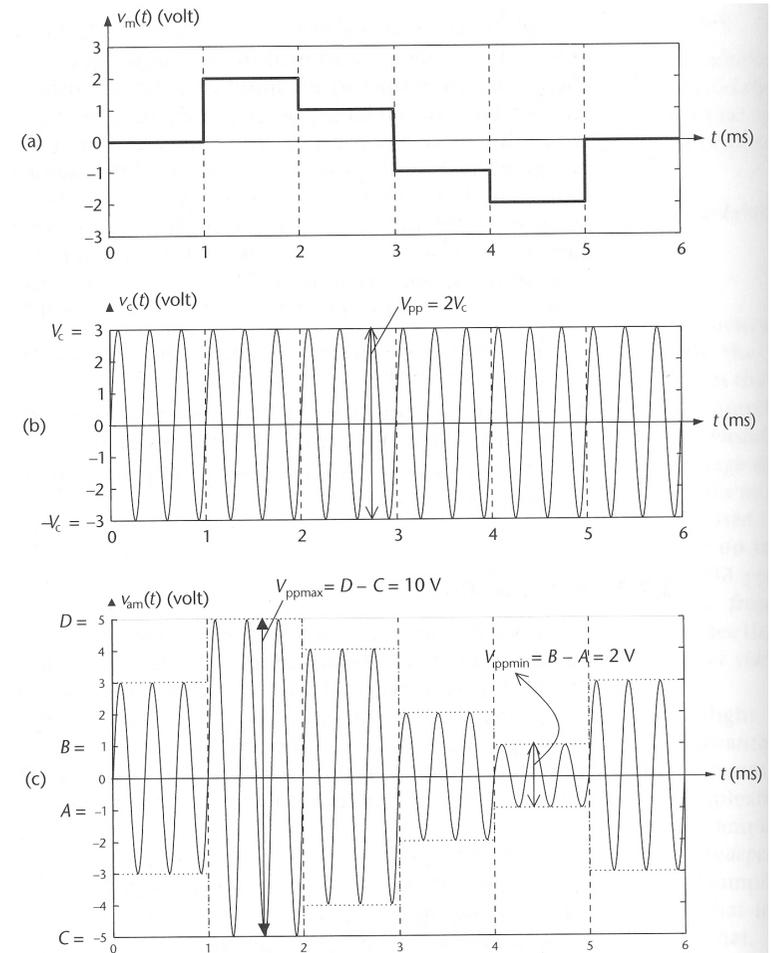


Figure 3.1 (a) Message signal; (b) carrier signal; (c) AM signal, with modulation sensitivity  $k = 1$  volt/volt.

## Amplitude modulation (CEP 3.2.1 and 3.2.3)

- **Modulation factor**  $m = \frac{V_{ppmax} - V_{ppmin}}{V_{ppmax} + V_{ppmin}}$
- **Modulation index** is modulation factor expressed as a percentage.
- **Undermodulation** occurs when  $m < 100\%$
- **100% modulation** occurs when  $m = 100\%$
- **Overmodulation** occurs when  $V_c + k_{am}v_m(t) < 0$ , preventing envelope detection.

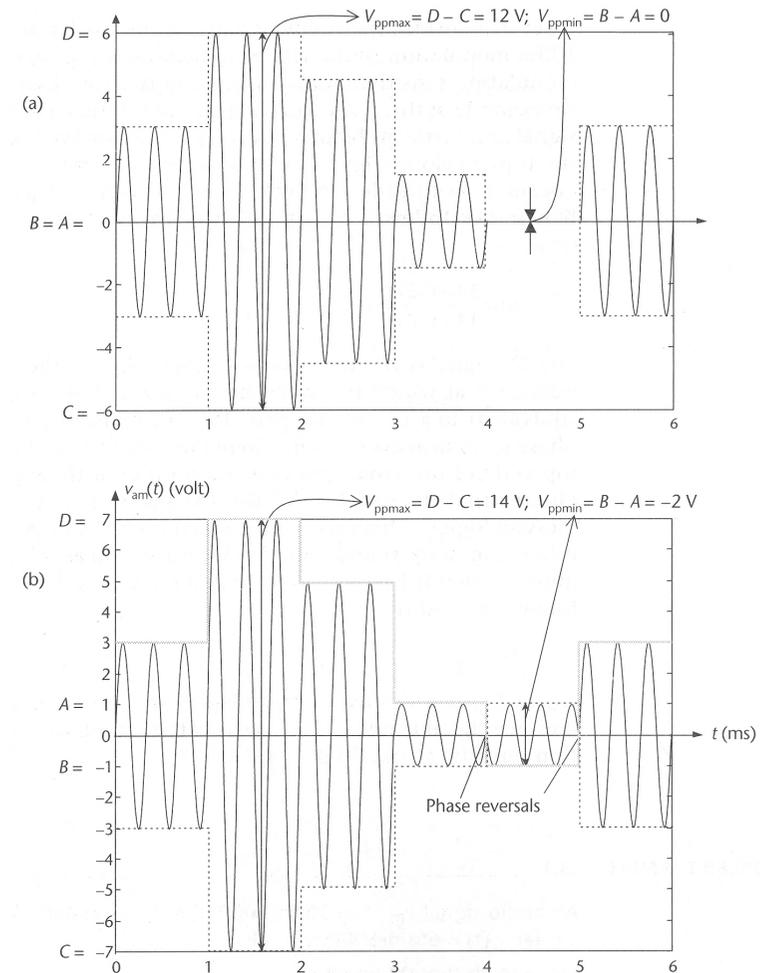


Figure 3.3 AM signal with (a) 100% modulation; (b) over-modulation.

# Amplitude modulators (CEP 3.4)

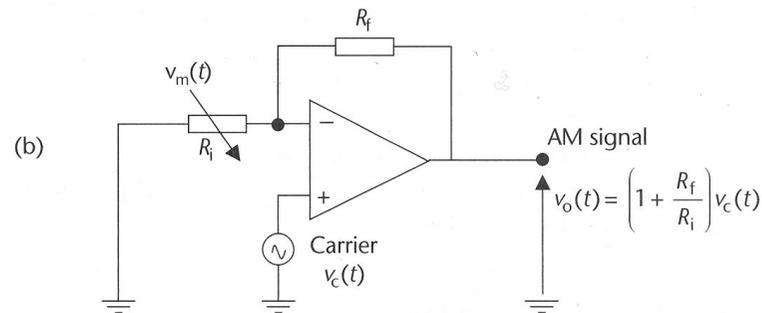
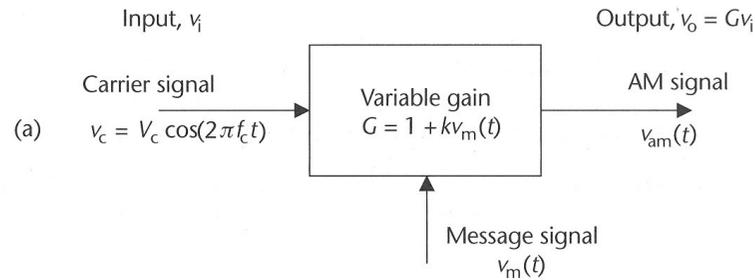


Figure 3.13 (a) AM generation using a variable gain device; (b) opamp implementation.

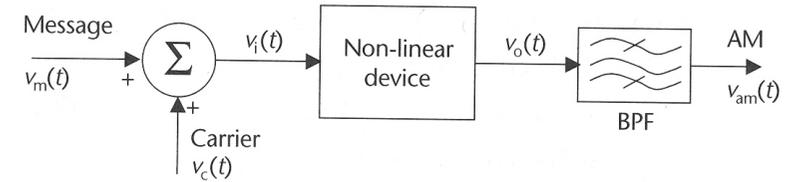
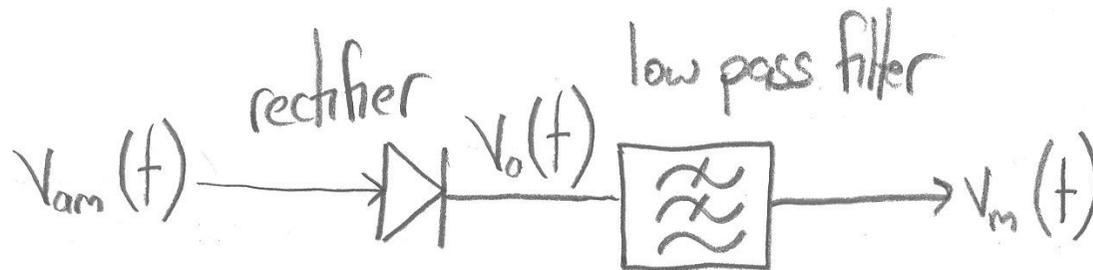


Figure 3.14 Square-law and switching (AM) modulator.

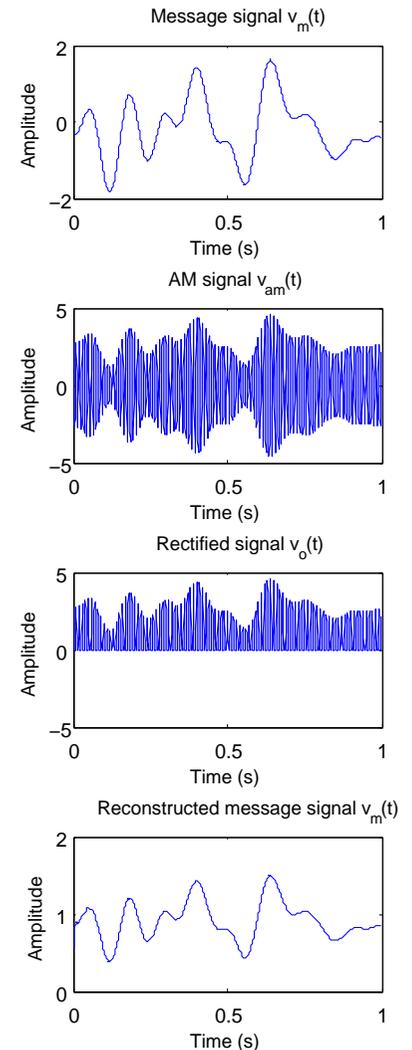
- Diodes or transistors are used for the **Non-Linear Device (NLD)**.
- In a **switching modulator**, the NLD switches the signal on and off at the carrier frequency. Here,  $v_o(t) = v_i(t)v_s(t)$ , where  $v_s(t)$  is a square wave.
- In a **square law modulator**, the resistance of the non-linear device depends on the input voltage. Here,  $v_o(t) = av_i(t) + bv_i^2(t)$ .
- In both cases, the band-pass filter is centred on the carrier frequency.

In a **linearly varied gain modulator**,  $R_i$  is provided by a **Field Effect Transistor (FET)**, where  $R_i = \frac{1}{av_m(t)}$ .

## Amplitude demodulation (CEP 3.5.1)



- If the AM signal is not overmodulated, **envelope detection** can be used.
- This is **non-coherent** because it does not require exact knowledge of the carrier frequency or phase.
- The **rectifier** removes the negative-going part of the signal.
- The **Low Pass Filter** (LPF) smooths out the oscillations.
- The LPF cut-off frequency should be between the maximum frequency in the signal  $f_{max}$  and the carrier frequency  $f_c$ . The lower it is, the more channel-induced noise that can be removed.



# Diode demodulator

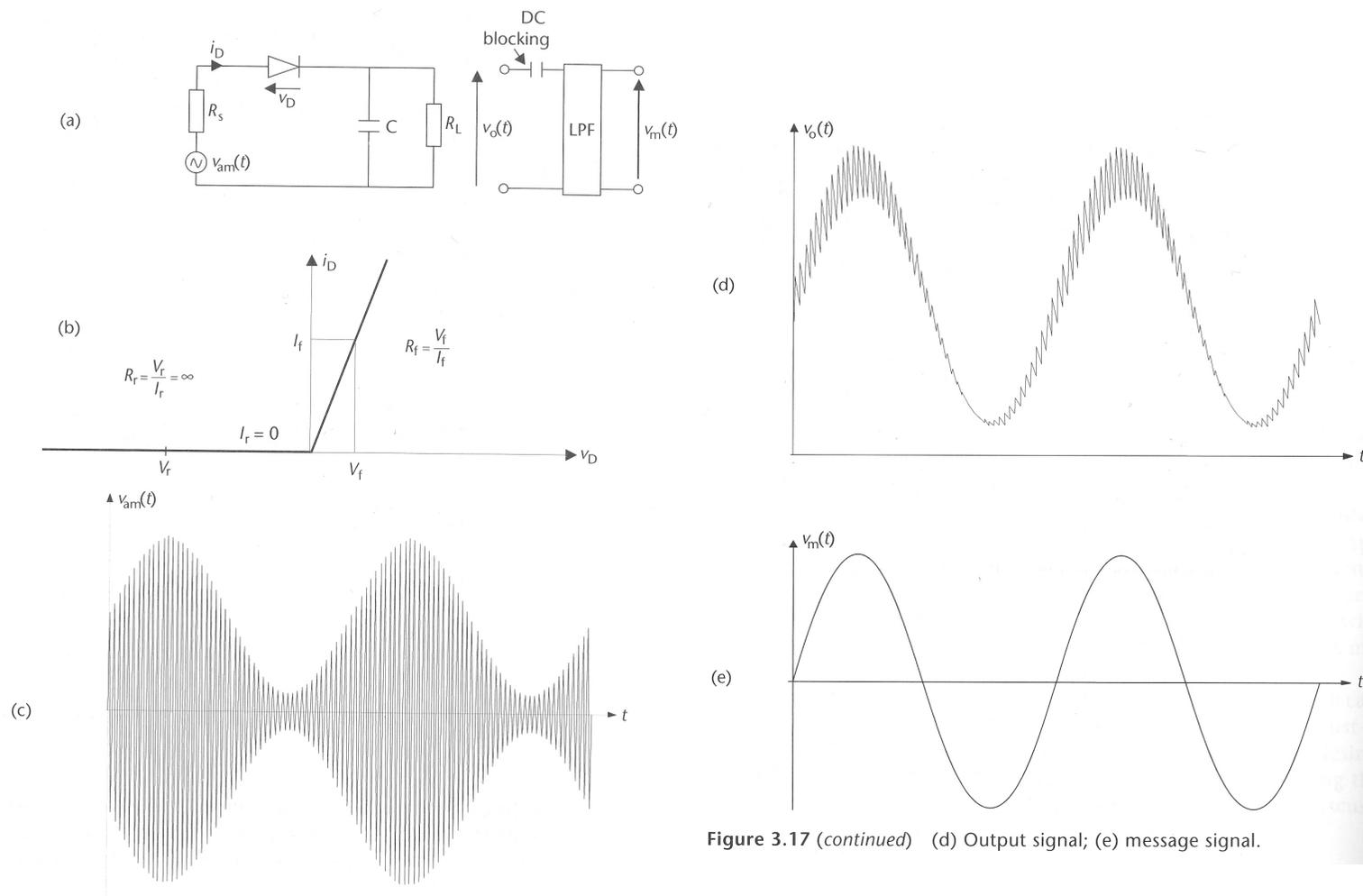
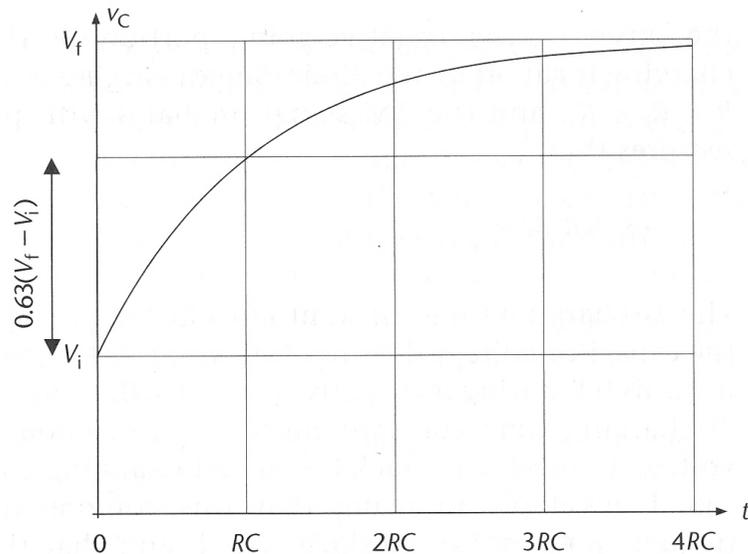


Figure 3.17 (continued) (d) Output signal; (e) message signal.

Figure 3.17 Diode demodulator: (a) circuit; (b) ideal diode characteristic; (c) input AM signal (continues overleaf).

## Diode demodulator

$$v_C(t) = V_f - (V_f - V_i) \exp\left(-\frac{t}{RC}\right)$$



**Figure 3.18** Exponential rise in voltage across a capacitor  $C$  that is charging through resistor  $R$  from an initial voltage  $V_i$  towards a final voltage  $V_f$ .

- We need the capacitor to charge quickly through  $R_f$  and  $R_s$ , so that the voltage will follow the rising edges of the carrier wave.

$$(R_f + R_s)C \ll 1/f_c$$

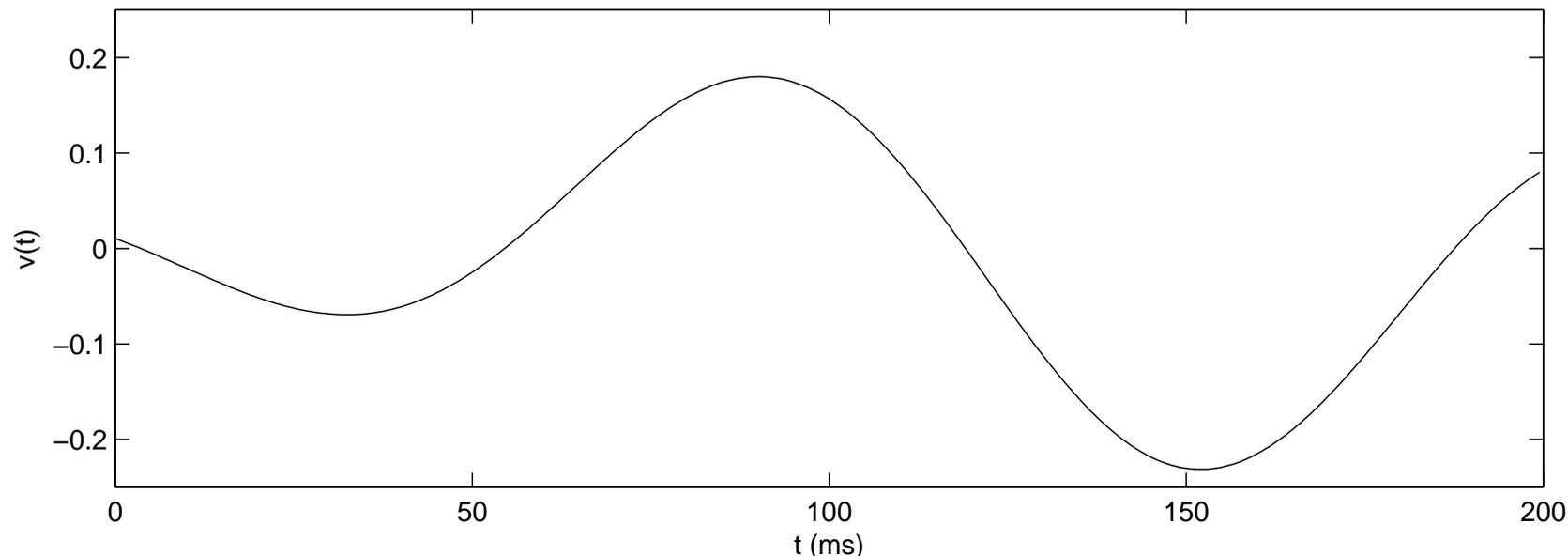
- We need the capacitor to discharge quickly through  $R_L$ , so that the voltage will follow the falling part of the envelope

$$R_L C \ll 1/f_{max}$$

- ...but not quick enough for the voltage to follow the falling edges of the carrier wave

$$R_L C \gg 1/f_c$$

## Exercise



1. In the first lecture, we considered the baseband modulation of this signal. In order to perform digital baseband modulation, we converted the signal into a bit sequence. Sketch OOK, BFSK and BPSK **digital carrier modulations** of this bit sequence, remembering to annotate the time axes.
2. Also, sketch the result of using an  $f_c = 400$  Hz carrier and AM **analogue carrier modulation** to convey this signal, which contains a maximum frequency of  $f_{max} = 10$  Hz. What is the DC offset, modulation sensitivity and modulation index in your sketch?

## Exercise continued

3. For a **linearly varied gain modulator** using a FET for which  $a = 2$ , choose a value for the carrier amplitude  $V_c$  and the resistor value  $R_f$  that will AM modulate the signal with the same DC offset and modulation sensitivity that you used in your sketch.
4. For a **diode demodulator** in which  $R_s = 50 \Omega$  and  $R_f = 20 \Omega$ , determine values for the capacitor  $C$  and load resistor  $R_L$  which will allow your AM signal to be demodulated.