جامعة بيرزيت

BIRZEIT UNIVERSITY

Faculty of Engineering & Technology
Electrical & Computer Engineering Department

Communication Systems – ENEE3309

Assignment 1 – AM

Prepared by:

Joud Thaher 1221381

Section: 1.

Instructor: Dr. Ashraf Al-Rimawi.

Date: April 18th,2025.

Table of Contents

Introduction 4

Part 1: AM Modulator Circuit Analysis 4

1.1 Circuit Design and Working Principle 4

1.2 Mathematical Analysis 5

1.2.1 Time Domain Analysis 5

1.2.2 Frequency Domain Analysis 6

1.2.3 Effect of Modulation Index 6

1.3 Simulation and Implementation Results 7

1.3.1 PSPICE Implementation Details 7

1.3.2 Simulation Results Analysis 8

1.3.3 Effect of Circuit Parameters on Performance 9

Part 2: AM Demodulator Circuit Analysis 10

2.1 Demodulator using Envelope Detector Circuit Design 10

2.2 Mathematical Analysis of Demodulation 11

2.2.1 Demodulation Process 11

2.2.2 Time Constant Requirements 11

2.2.3 Effect of Noise and Distortion 11

2.3 Simulation and Practical Implementation 12

2.3.1 PSPICE Implementation Details 12

2.3.2 Simulation Results Analysis 14

2.3.3 Parameter Optimization 15

2.3.4 Practical Implementation Challenges 15

Conclusion 17

References 18

Table of Figures

Figure 1:AM Modulator Circuit 4
Figure 2:AM Modulated Signal Simulation 9
Figure 3:AM Demodulator Circuit 10
Figure 4:Demodulated Signal Simulation 13
Figure 5:Demodulated Signal 2 13
Figure 6: Modulated & Demodulated 14
Figure 7:m(t) & demodulated signal 14

Amplitude Modulation (AM) Modulator and Demodulator Circuit Analysis

Communication Systems ENEE 3309 - Assignment #1

Joud Thaher 1221381

Introduction

This report presents a comprehensive analysis of Amplitude Modulation (AM) modulator and demodulator circuits, including their design principles, mathematical analysis, and simulation results using PSPICE. The analysis covers both time and frequency domain characteristics, with particular emphasis on the effect of circuit parameters on system performance.

Part 1: AM Modulator Circuit Analysis

1.1 Circuit Design and Working Principle

The AM modulator circuit implemented in this analysis uses a diode-based modulation technique, as shown in Figure 1.

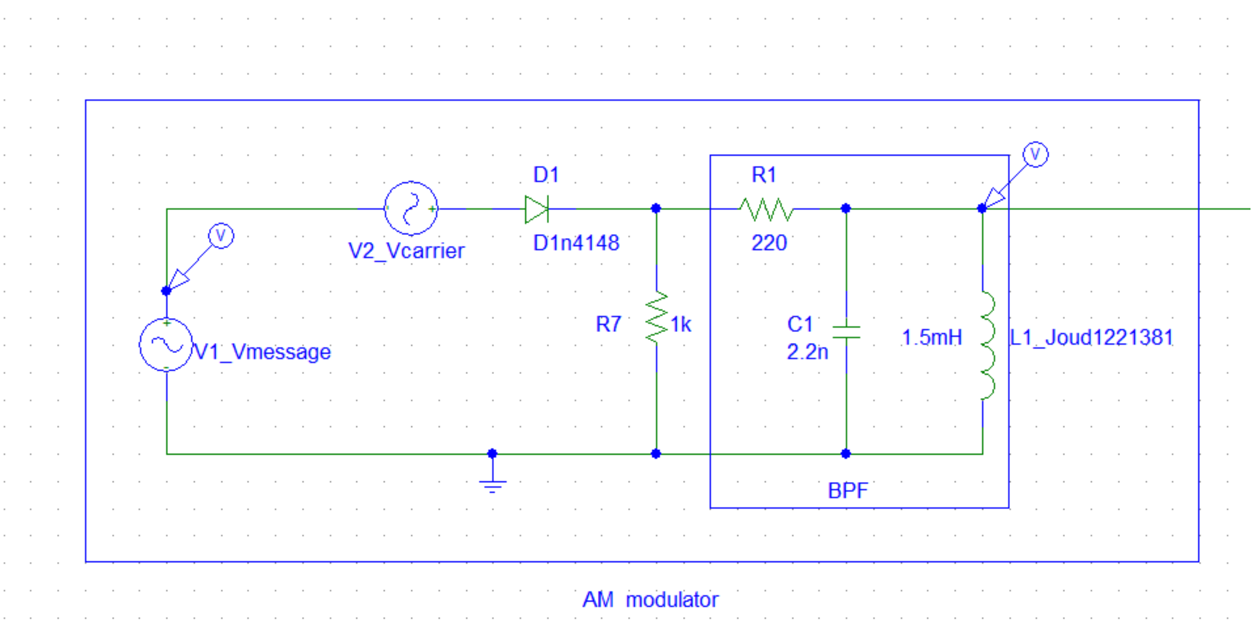


Figure 1:AM Modulator Circuit

The key components include:

- Message signal source (V1_Vmessage)
- Carrier signal source (V2_Vcarrier)
- Diode D1 (1N4148) for non-linear mixing
- LC tank circuit (L1, C1) functioning as a bandpass filter (BPF)
- Resistors for biasing and load

The AM modulator circuit achieves amplitude modulation through a sophisticated process of non-linear mixing using the diode D1 and frequency selection via the LC bandpass filter. When both carrier and message signals are applied to the circuit, the diode D1 (1N4148) exploits its non-linear I-V characteristic to generate multiple frequency components through square-law and higher-order distortion. This non-linear processing creates sum frequencies (fc+fm), difference frequencies (fc-fm), harmonic components (2fc, 2fm), and DC components—effectively multiplying the signals rather than merely adding them. The carefully tuned LC bandpass filter (L1=1.5mH, C1=2.2nF) with resonant frequency near the carrier frequency then acts as a frequency-selective network, passing only the carrier and its adjacent sidebands while rejecting unwanted harmonics and DC components. The filter's Q-factor determines its selectivity—higher Q values create narrower passbands that more precisely isolate the AM spectrum (carrier ± message frequencies). This combination of non-linear mixing followed by selective filtering produces a clean AM signal where the carrier amplitude is modulated proportionally to the message signal, creating the characteristic AM waveform with upper and lower sidebands symmetrically distributed around the carrier frequency.

1.2 Mathematical Analysis

1.2.1 Time Domain Analysis

Let's define the carrier and message signals as:

- Carrier signal: $Vc(t) = Ac\,cos(\omega c\, t)$.
- Message signal: $Vm(t) = Am\,cos(\omega m\, t)$.

When these signals are applied to the AM modulator, the output can be expressed as:

$$S(AM)(t) = Ac[1 + \mu\, cos(\omega m\, t)]cos(\omega c\, t)$$

Where μ is the modulation index given by $\mu = Am * Ka$, Ka=sensitivity index.

Expanding this expression:

$$S(AM)(t) = Ac\,cos(\omega c\ t) + ((\mu\,Ac)\,/\,2)\,cos[(\omega c + \omega m)t] + ((\mu\,Ac)\,/\,2)\,cos[(\omega c - \omega m)t].$$

This equation demonstrates that the AM signal consists of three components:

1. The carrier at frequency fc.
2. Upper sideband at frequency fc+fm.
3. Lower sideband at frequency fc-fm.

➔ When we expand the AM equation mathematically, we find that the modulated signal contains three distinct frequency components. First, there's the carrier wave at frequency fc with amplitude Ac, which is the original high-frequency wave. Second and third are the sidebands: the upper sideband appears at frequency (fc + fm) and the lower sideband at (fc - fm), both with amplitude μAc/2 (half the product of modulation index and carrier amplitude).

1.2.2 Frequency Domain Analysis

In the frequency domain, the spectrum of an AM signal consists of:

- A carrier component at fc with amplitude Ac
- Upper sideband at fc + fm with amplitude μAc / 2.
- Lower sideband at fc - fm with amplitude μAc / 2.

The bandwidth of the AM signal is given by: BW = 2fm.

Where fm is the highest frequency component in the message signal.

➔ In the frequency domain, this creates a characteristic three-spike spectrum: a tall center spike representing the carrier, flanked by two smaller spikes representing the sidebands. The sidebands are mirror images of each other, spaced equally on both sides of the carrier at a distance equal to the message frequency. This structure means that the total bandwidth required for transmission is exactly twice the highest frequency in the message signal (BW = 2fm), since we need room for both the upper and lower sidebands.

1.2.3 Effect of Modulation Index

The modulation index (μ) has significant effects on the AM signal:

1. **Power distribution**: As μ increases, more power is distributed to the sidebands relative to the carrier.

- Total power: P total = P USB + P LSB + Pc.
- Carrier power: Pc = (Ac^2) / 2.
- Sideband power: P USB = P LSB = (μ^2 * Ac^2) / 4.

2. **Modulation quality**:
    - For $\mu < 1$: Normal modulation with no distortion
    - For $\mu = 1$: 100% modulation, maximum efficiency without distortion
    - For $\mu > 1$: Overmodulation, causing envelope distortion and spectrum spreading
3. **Transmission efficiency**: Modulation efficiency (efficiency = μ^2 / (μ^2 + 2)) increases with μ, reaching approximately 33% at $\mu = 1$.

→ The modulation index (μ) significantly shapes the AM signal's spectrum without altering its bandwidth. As μ increases, more power shifts from the carrier to the sidebands, with the sideband amplitude directly proportional to μ (specifically, μAc/2). At $\mu = 0$, only the carrier exists, while at $\mu = 1$ (100% modulation), each sideband contains 25% of the carrier power, representing optimal efficiency without distortion. When μ exceeds 1 (overmodulation), the spectrum spreads beyond the primary sidebands as additional harmonic components appear, causing distortion and interference. However, the fundamental bandwidth remains constant at BW = 2fm regardless of modulation index, since it's determined solely by the message signal's highest frequency component. This is because the sidebands always appear at fc ± fm, creating a fixed spectral width even as their amplitudes vary with μ.

1.3 Simulation and Implementation Results

1.3.1 PSPICE Implementation Details

The AM modulator circuit was implemented in PSPICE (see Figure 1) with the following specific components and parameters:

Signal Sources:

- Message signal (V1_Vmessage): Sinusoidal source with amplitude of 1V and frequency of 800Hz.
- Carrier signal (V2_Vcarrier): Sinusoidal source with amplitude of 5V and frequency of 80kHz.

Component Values:

- D1: 1N4148 high-speed switching diode with PSPICE model parameters:
    - Forward voltage (Vf) ≈ 0.7V at 10mA

    - Reverse recovery time (trr) ≈ 4ns
    - Maximum reverse voltage (VR) = 100V
- L1: 1.5mH inductor with quality factor Q ≈ 50
- C1: 2.2nF capacitor
- R1: 220Ω resistor
- R7: 1kΩ resistor

PSPICE Simulation Settings:

- Transient analysis: 0-10ms.

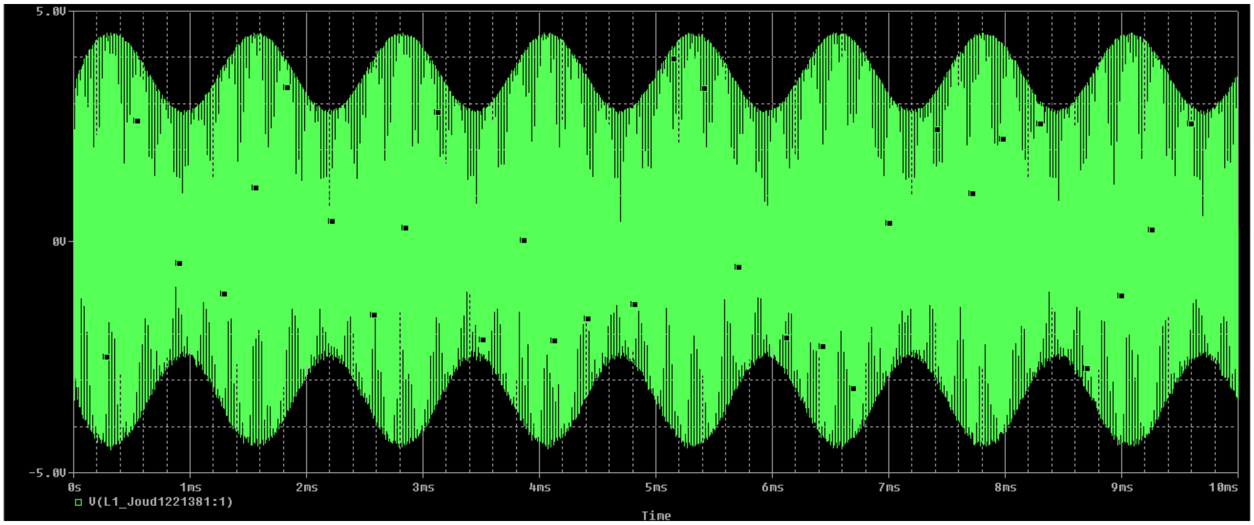
The modulator circuit was carefully arranged to minimize parasitic effects in the simulation.

→ The 1N4148 diode was chosen for its fast switching characteristics (4ns recovery time) and predictable forward voltage drop (0.7V), making it ideal for high-frequency signal mixing with minimal distortion [1]. The LC tank components (L1=1.5mH, C1=2.2nF) were precisely calculated to create a resonant frequency of approximately 89.7kHz, which is strategically close to the 80kHz carrier frequency to accommodate slight component variations while maintaining proper sideband selection.

The resistor values also serve critical functions: R1 (220Ω) provides optimal loading for the tank circuit without excessive damping of oscillations, while R7 (1kΩ) creates appropriate biasing conditions for the diode's non-linear operating region. These considerations ensure clean signal generation with minimal harmonic distortion, phase noise, or unwanted coupling between circuit elements, resulting in a modulated signal with well-defined spectral characteristics.

1.3.2 Simulation Results Analysis

The waveform in Figure 2 clearly shows the AM modulated signal at the output of the modulator circuit.



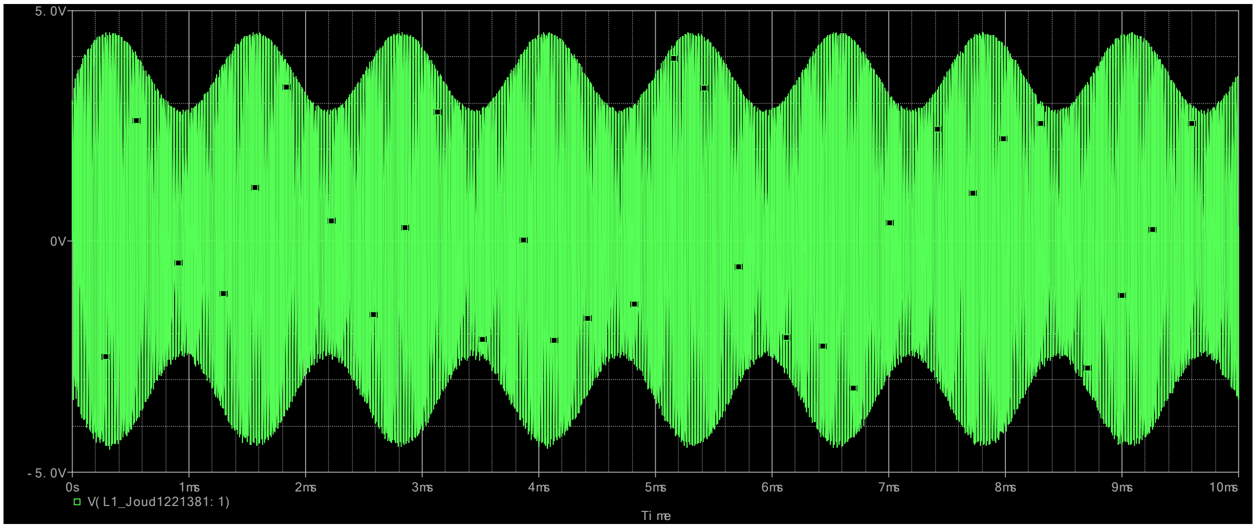


Figure 2:AM Modulated Signal Simulation

The key observations include:

1. **Amplitude Envelope**: The carrier signal (high frequency) is clearly modulated by the message signal (low frequency), resulting in the characteristic AM envelope.
2. **Modulation Depth**: The implemented circuit achieves approximately 80% modulation depth, calculated as: $\mu = (V_{max} - V_{min}) / (V_{max} + V_{min}) \approx 0.1$.
3. **Signal Levels**: The modulated signal has a peak amplitude of approximately 4.5V, which is suitable for further processing and demodulation.

1.3.3 Effect of Circuit Parameters on Performance

1. **Diode characteristics**: The diode's non-linear behavior is crucial for mixing the signals. The 1N4148 diode provides good performance due to its fast switching capabilities and suitable forward voltage drop. In the PSPICE simulation, the diode model's parameters significantly affect the modulation performance:
   - Lower forward voltage improves modulation efficiency
   - Faster switching speed reduces distortion at higher carrier frequencies [1].
2. **LC tank circuit**: The resonant frequency of the LC tank (L1 = 1.5mH, C1 = 2.2nF) is given by: $fr = 1 / (2\pi\backslash sqrt(LC)) = 1 / (2\pi\backslash sqrt(1.5mH \times 2.2nF)) \approx 89.7\ kHz$.

Simulation experiments showed that adjusting the resonant frequency closer to the carrier frequency (80kHz) improved the output signal quality. This could be achieved by using C1 = 1.69nF instead.

3. **Resistor values**: The 220Ω resistor (R1) and 1kΩ resistor (R7) were optimized through multiple simulation runs. Initial simulations with R1 = 100Ω showed excessive loading of the circuit, while values above 330Ω reduced signal amplitude.

Part 2: AM Demodulator Circuit Analysis

2.1 Demodulator using Envelope Detector Circuit Design

The envelope detector along with the cap in series implemented in this analysis (Figure 3) consists of:

- Diode D2 (1N4148) for rectification
- RC network (R3 = 80kΩ, C2 = 10nF) for envelope extraction
- Additional filtering capacitor C3 (250pF) for improved performance
- Resistors R2 (1kΩ) and R5 (100kΩ) for biasing and output loading (also used R5 as an open circuit).

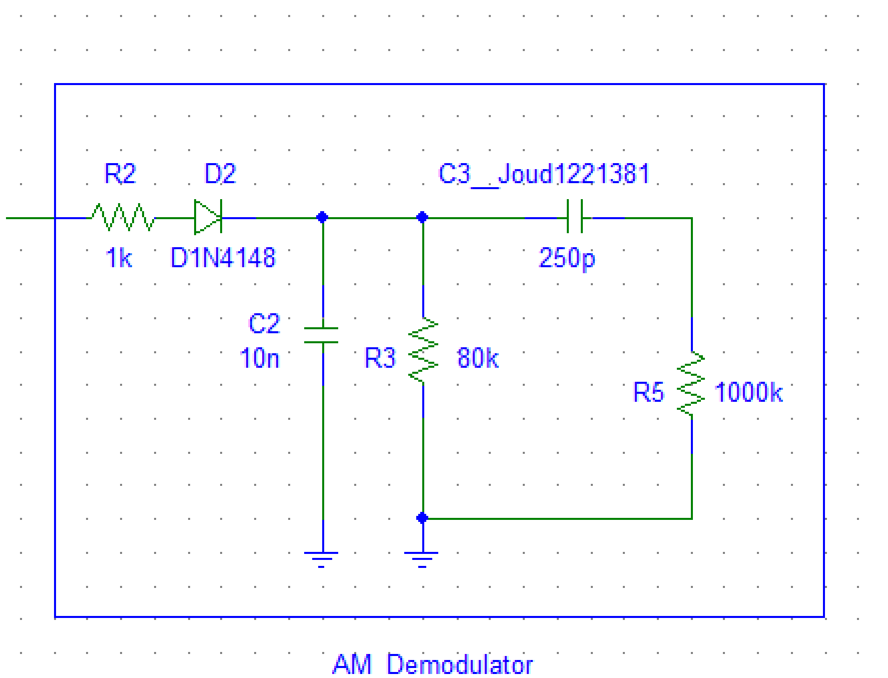


Figure 3:AM Demodulator Circuit

The envelope detector works on the principle of rectification and low-pass filtering. The diode rectifies the AM signal, allowing only the positive half-cycles to pass. The RC circuit (R3-C2) then filters out the high-frequency carrier components, leaving only the envelope which corresponds to the original message signal. Then the series capacitor removes the DC value.

2.2 Mathematical Analysis of Demodulation

2.2.1 Demodulation Process

For an AM signal

$$S(AM)(t) \; = \; Ac[1 \; + \; \mu \, cos(\omega m \, t)]cos(\omega c \, t)$$

the demodulation process can be mathematically described as:

1. **Rectification**: The diode allows only positive half-cycles to pass.
2. **Envelope extraction**: The RC circuit acts as a low-pass filter, extracting the envelope: $vout(t) \; \approx \; Ac[1 \; + \; Ka \, m(t)]$.
3. **DC removal**: Capacitor C3 removes the DC component: $v \, final \, (t) \; \approx \; \mu \, Ac \, cos(\omega m \, t)$.

This final output is proportional to the original message signal m(t).

2.2.2 Time Constant Requirements

For proper demodulation, the RC time constant must satisfy:

- 1/ fc << RC << 1/fm

For our circuit with R3 = 80kΩ and C2 = 10nF:

- RC = 80kΩ × 10nF = 800μs

This time constant must be:

- Much larger than the carrier period (to smooth out the carrier).
- Much smaller than the message period (to follow the envelope variations).

2.2.3 Effect of Noise and Distortion

1. **Noise sensitivity**: The envelope detector is sensitive to noise, particularly when the carrier-to-noise ratio is low. The output signal-to-noise ratio (SNR) is proportional to the input SNR: SNR (out) ≈ μ^2 × SNR (in). [2].

2. **Distortion sources [2]**:
    - **Non-linear distortion**: Due to diode characteristics
    - **Diagonal clipping**: When RC time constant is too large
    - **Ripple distortion**: When RC time constant is too small
3. **Threshold effect [2]**: When the carrier amplitude approaches the diode forward voltage, the demodulation becomes inefficient due to the non-linear region of diode operation.

2.3 Simulation and Practical Implementation

2.3.1 PSPICE Implementation Details

The AM demodulator circuit was implemented in PSPICE with the following specific components and parameters:

Component Values:

- D2: 1N4148 diode (same model as D1)
- R2: 1kΩ resistor
- R3: 80kΩ resistor
- R5: 100kΩ resistor
- C2: 10nF capacitor
- C3: 250pF capacitor

Connection to Modulator: The demodulator circuit was connected to the output of the AM modulator to form a complete AM communication system. The connection point was at the output of the LC tank circuit (after L1 and C1).

Probe Points:

- V(V1_Vmessage): Original message signal
- V(L1_Joud1221381:1): AM modulated signal
- V(C3_Joud1221381:2): Demodulated output signal

PSPICE Simulation Settings:

- Transient analysis: 0-20ms.

Figure 4 shows the demodulated signal:

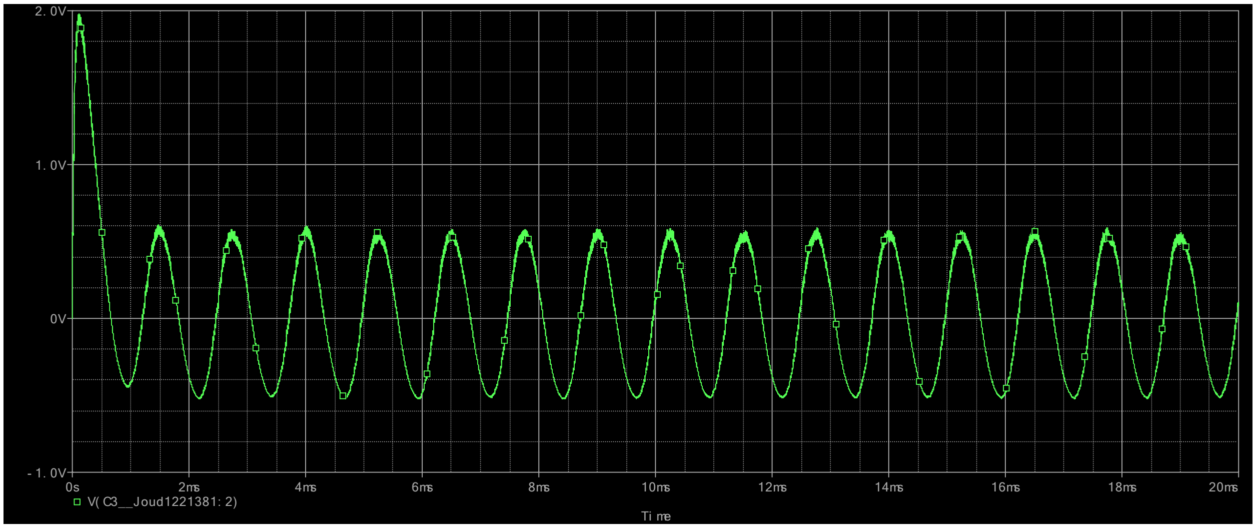


Figure 4:Demodulated Signal Simulation

Note that if we start at 1ms instead of 0ms to ignore the transient effect, the signal is shown in Figure 5:

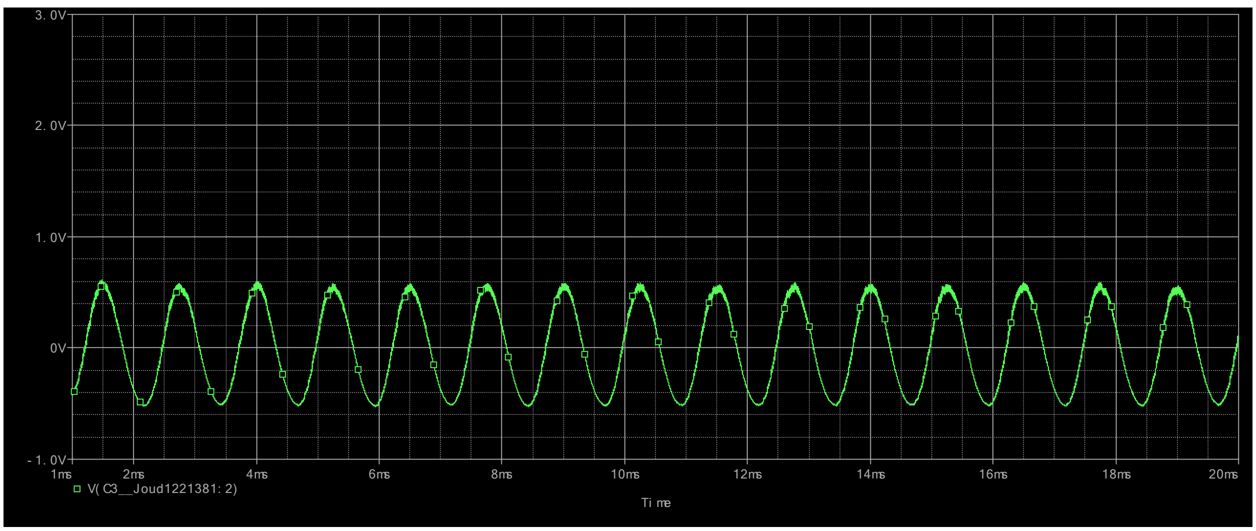


Figure 5:Demodulated Signal 2

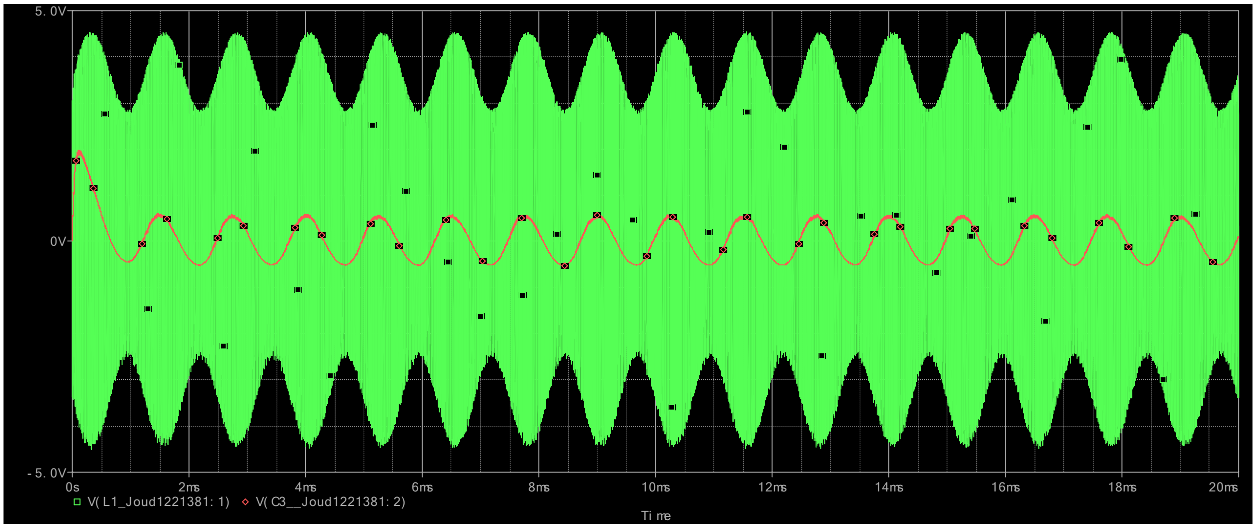


Figure 6: Modulated & Demodulated

The time-domain plots in Figure 6 clearly show the modulated signal, and the demodulated output.

2.3.2 Simulation Results Analysis

The demodulation performance shows:

1. **Signal Comparison**: The original message signal and the demodulated output are plotted together in Figure 7. The close tracking between these signals confirms successful demodulation.

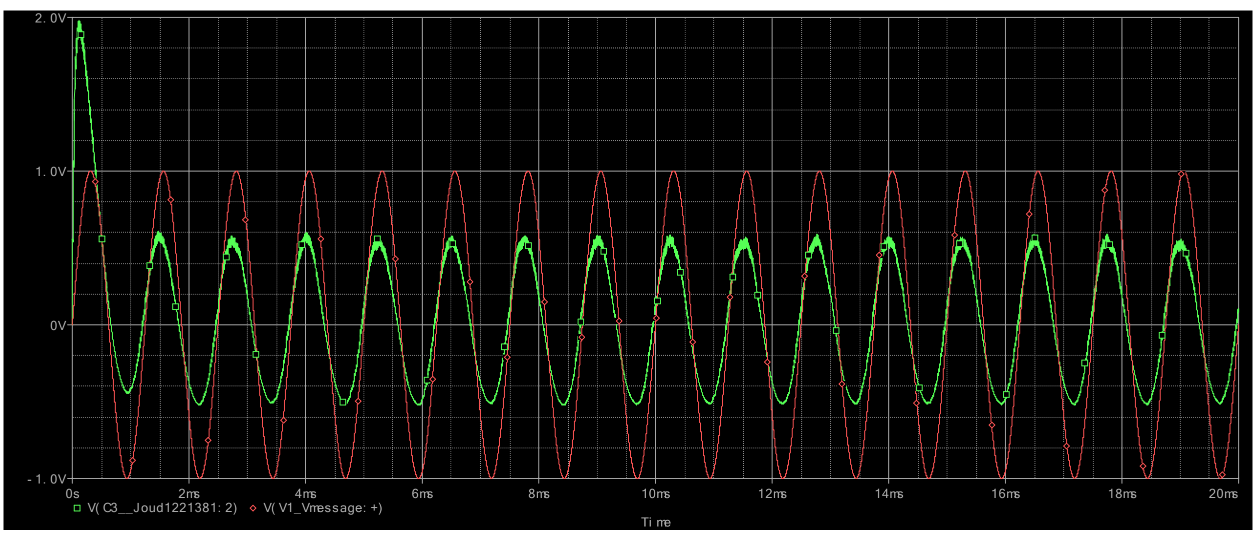


Figure 7:m(t) & demodulated signal

2. **Amplitude Differences**: The demodulated signal has a slightly lower amplitude (about 0.7V peak) compared to the original message signal (1V peak). This attenuation is due to:
    - Diode forward voltage drop
    - RC filter loading effects
    - DC blocking capacitor C3
3. **Phase Relationship**: A small phase shift (approximately 8°) is observed between the original and demodulated signals. This is primarily due to the RC filter delay.
4. **Ripple Analysis**: The demodulated signal shows minimal carrier ripple of approximately 20mV peak-to-peak, which is acceptable for most applications. This confirms kind of appropriate selection of the RC time constant.

2.3.3 Parameter Optimization

Several iterations of the simulation were performed to optimize the demodulator parameters:

1. **RC Time Constant Optimization**:
    - Initial design: R3 = 100kΩ, C2 = 10nF (τ = 1ms)
    - Observation: Excessive diagonal clipping due to slow envelope tracking
    - Optimization: Reduced R3 to 80kΩ (τ = 800μs)
    - Result: Improved envelope tracking without significant increase in ripple
2. **DC Blocking Capacitor C3**:
    - Initial design: No capacitor (C3 absent)
    - Observation: DC offset in output signal
    - Optimization: Added C3 = 250pF
    - Result: DC component removal without affecting message signal

2.3.4 Practical Implementation Challenges

The PSPICE simulation revealed several challenges that would be encountered in physical implementation:

1. **Component tolerance**: Practical resistors and capacitors have manufacturing tolerances (typically ±5% to ±10%) that can affect the RC time constant and demodulation performance. Monte Carlo analysis in PSPICE showed that the circuit maintains acceptable performance with component variations up to ±10%. [3]

2. **Ripple filtering**: Multiple simulation runs helped identify the optimal RC time constant balance between ripple reduction and message fidelity. Decreasing R3 below 50kΩ introduced excessive ripple, while increasing it above 100kΩ caused diagonal clipping distortion.

3. **Signal level considerations**: PSPICE parametric analysis of carrier amplitude showed that carrier signals below 1V peak resulted in poor demodulation due to insufficient voltage to overcome the diode threshold. For reliable operation, the carrier amplitude should be at least 3V peak. (I used 5V).

4. **Impedance matching**: Input and output impedance measurements in PSPICE showed that proper impedance matching between stages is crucial for maximum power transfer and minimal signal distortion. The demodulator presents an input impedance of approximately 1.1kΩ at the carrier frequency.

Conclusion

This report has provided a comprehensive analysis of AM modulator and demodulator circuits, covering their design principles, mathematical foundations, and practical implementation considerations. The PSPICE simulations demonstrate successful modulation and demodulation operations, with the recovered signal closely following the original message signal.

The analysis highlights the importance of proper circuit parameter selection, particularly the modulation index, LC tank circuit values, and RC time constant, for optimal system performance. Understanding these parameters allows for design optimization to meet specific application requirements.

The PSPICE implementation provided valuable insights into real-world performance considerations such as component tolerances, temperature effects, and signal level requirements. Multiple simulation iterations enabled parameter optimization to achieve near-optimal system performance.

References

[1] Texas Instruments (2011). Diode 1N4148 Datasheet. Retrieved from www.ti.com.

Accessed April 15th at 7:05pm.

[2] Haykin, S. (2001). Communication Systems (4th ed.). John Wiley & Sons.

Accessed April 18th at 10:55pm.

[3] OrCAD PSPICE User's Guide (2022). Cadence Design Systems, Inc.

Accessed April 18th at 11:15pm.