Voltage-Controlled Attenuators and Amplifiers using Forward-biased Diodes

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***Abstract*—This paper presents a comprehensive study and experimental validation of voltage-controlled attenuators and amplifiers using forward-biased diodes. Through the practical application of DC biasing techniques and the implementation of a small-signal (linear) model, I explore the impact of varying the saturation current (I_S), ideality factor (n), and thermal voltage on the performance of electronic circuits. Utilizing a dual operational amplifier IC, specifically the LM358P, alongside a small-signal diode, such as the BAT81S-TR, I construct and characterize both a voltage-controlled attenuator and a non-inverting amplifier. The attenuator circuit effectively modulates AC signal amplitude, while the amplifier's gain is adjusted via DC voltage, demonstrating the correlation between the diode's dynamic resistance and the gain-bandwidth product.**

***Index Terms*—DC biasing, operating point, small-signal model, diode, saturation current, ideality factor, thermal voltage, dynamic resistance, gain-bandwidth product, voltage-controlled attenuator, non-inverting amplifier.**

I. Introduction

Voltage control of electronic signals is fundamental in numerous applications, ranging from simple audio adjustments to complex signal processing in communication systems. The use of diodes, particularly in configurations that exploit their non-linear characteristics, enables the development of circuits like voltage-controlled attenuators and amplifiers. These devices play crucial roles in modulating signal amplitude and gain, respectively, based on external voltage inputs.

This study delves into the theory and practical implementation of such devices using forward-biased diodes. By incorporating DC biasing techniques, I analyze how the diode's saturation current (I_S), ideality factor (n), and thermal voltage (V_T) influence circuit behavior. This approach allows for a nuanced understanding of the diode's dynamic resistance and its effect on circuit functionality.

The experimental section utilizes a dual op-amp IC, the LM358P, and a small-signal diode, exemplified by the BAT81S-TR, to construct a voltage-controlled attenuator and a non-inverting amplifier. The attenuator circuit demonstrates how signal amplitude can be precisely controlled through voltage, while the amplifier showcases adjustable gain, highlighting the relationship between diode characteristics and signal amplification.

My investigation aims to provide insights into the practical applications of diodes in signal modulation, emphasizing the importance of understanding electronic component behavior for circuit design and optimization.

II. Background and Preliminaries

The fundamental principles underlying the operation of voltage-controlled attenuators and amplifiers revolve around the electrical characteristics of diodes and operational amplifiers (op-amps). Diodes, semiconductor devices known for allowing current to flow in one direction while blocking it in the opposite direction, exhibit a non-linear voltage-current (V-I) relationship. This non-linearity, governed by the diode equation, becomes the basis for designing circuits that can modulate signal amplitude and gain in response to voltage changes.

A. Diode Characteristics

A key aspect of diode behavior is its forward-bias operation, where the diode conducts electricity. The current through a diode can be described by the Shockley diode equation:

$$I_D = I_S(e^{\frac{V_D}{nV_T}} - 1)$$

where I_D is the diode current, I_S is the saturation current, V_D is the voltage across the diode, n is the ideality factor (typically ranging from 1 to 2), and V_T is the thermal voltage (approximately 26 mV at room temperature).

The diode's dynamic resistance (r_d), a crucial parameter in designing voltage-controlled devices, is derived from the diode's I-V characteristics as follows:

$$r_d = \frac{dV_D}{dI_D} = \frac{nV_T}{I_D}$$

This expression highlights how r_d varies with the operating current, impacting the device's response to signal changes.

B. Operational Amplifiers

Operational amplifiers, integral to amplifying circuits, can be configured in numerous ways to achieve different functionalities. A non-inverting amplifier, for example, uses feedback to set the gain of the circuit, which can be dynamically adjusted in voltage-controlled applications.

C. Circuit Design Principles

The design of voltage-controlled attenuators and amplifiers incorporates these components within specific configurations to achieve desired behaviors. Attenuators reduce the amplitude of an incoming signal based on a control voltage, often utilizing the diode's dynamic resistance, which varies with the current flowing through it. Amplifiers, on the other hand, can increase the signal amplitude, with the gain controlled by an external voltage.

D. Dynamic Resistance and Circuit Analysis

Dynamic resistance (r_d) is a critical parameter for understanding the behavior of diodes in circuits. It is defined as the derivative of the voltage across the diode with respect to its current, indicating how the diode's voltage drop changes with varying current. This concept is crucial for analyzing the operation of both voltage-controlled attenuators and amplifiers, as it directly influences the signal modulation and amplification capabilities of these devices.

E. Model Parameter Extraction

Extracting the diode's model parameters, such as the saturation current (I_S) and the ideality factor (n), is essential for accurately simulating and predicting circuit behavior. These parameters are typically determined from the diode's V-I characteristics, which can be measured directly in the lab or obtained from manufacturer-supplied SPICE models. The accuracy of these parameters significantly affects the fidelity of circuit simulations and the effectiveness of the designed circuits in practical applications.

F. Voltage-Controlled Attenuator Design

The voltage-controlled attenuator utilizes a diode in conjunction with resistors and a capacitor to achieve variable attenuation of an AC signal. The key to its operation lies in the diode's dynamic resistance, which can be altered by adjusting the DC bias voltage across the diode. This principle allows for the precise control of signal amplitude, making it a versatile tool for signal processing applications.

G. Voltage-Controlled Amplifier Configuration

Building on the principles of the voltage-controlled attenuator, the voltage-controlled amplifier further demonstrates the utility of diodes in active circuit design. By incorporating the attenuator into a feedback loop of an operational amplifier, the circuit achieves adjustable gain. This configuration highlights the interplay between the diode's dynamic resistance and the operational amplifier's properties, such as the gain-bandwidth product, to modulate the amplifier's overall gain in response to changes in the control voltage.

H. Practical Considerations

Implementing these circuits requires careful consideration of component selection and circuit layout. The choice of diode, operational amplifier, and passive components can significantly impact the performance, reliability, and efficiency of the system. Additionally, practical issues such as temperature dependence, component tolerances, and signal integrity must be addressed to ensure the successful application of these voltage-controlled devices in real-world scenarios.

I. Solving the KVL for a Diode Circuit

To analyze the Voltage-Resistor-Diode (VRD) loop, especially under forward bias, iterative or numerical methods are often employed due to the transcendental nature of the diode equation. This approach is exemplified in the process of determining the diode's operating point, where the Kirchhoff's Voltage Law (KVL) is applied to a circuit including a diode, leading to equations that require iterative solutions for practical values of V_D and I_D.

III. Design

The design of voltage-controlled attenuators and amplifiers encompasses selecting appropriate components, determining circuit topology, and ensuring that the circuits meet specified performance criteria.

A. Component Selection

- **Diodes:** Small-signal diodes, such as the Schottky BAT81S-TR, were chosen for their low forward voltage drop and fast switching characteristics. These properties are essential for minimizing signal distortion and ensuring responsive control over the attenuation and amplification processes.
- **Operational Amplifiers:** The LM358P dual op-amp was selected for its versatility, availability, and compatibility with a wide range of supply voltages. Its characteristics, such as input offset voltage, bandwidth, and slew rate, were evaluated to ensure they match the requirements of the voltage-controlled amplifier design.
- **Passive Components:** Resistors and capacitors were chosen based on the required frequency response and impedance values. Precision resistors (1x10k, 1x100k, 2x200k) ensure accurate biasing and feedback, while a non-electrolytic capacitor in the range of 0.1μF to 1μF was selected for its stability and low leakage current, suitable for AC coupling and signal filtering applications.

B. Circuit Topology

- **Voltage-Controlled Attenuator:** The attenuator design incorporates a diode in a voltage-divider configuration with resistors, where the diode's dynamic resistance varies with the applied DC bias voltage. This variation allows for controlled attenuation of the AC signal passing through the circuit.

- **Voltage-Controlled Amplifier:** The amplifier circuit integrates the voltage-controlled attenuator within the feedback loop of an operational amplifier. This configuration enables the control of the amplifier's gain through adjustments in the DC bias voltage applied to the diode. The non-inverting amplifier setup was chosen to maintain signal phase and to facilitate ease of gain adjustment.

C. Simulation and Analysis

Prior to physical assembly, the circuits were simulated using software tools such as LTspice. These simulations helped in verifying the theoretical calculations, optimizing component values, and predicting the circuits' behavior under different operating conditions. The focus was on analyzing the frequency response, gain, and signal integrity to ensure that the designs would meet the expected performance metrics.

D. Experimental Validation

The designs were translated into physical circuits on breadboards for experimental validation. The process involved:

1) Constructing the circuits as per the schematics.
2) Adjusting the DC bias voltage to extract diode parameters and to observe the effects on attenuation and amplification.
3) Measuring the input and output signals using a two-input oscilloscope to verify the attenuation and gain values under various conditions.
4) Iteratively refining component values based on experimental results to fine-tune the circuit performance.

This hands-on experimentation provided invaluable insights into the practical aspects of circuit design, such as the impact of component tolerances and the importance of layout on circuit performance. Through this iterative design, simulation, and testing process, the voltage-controlled attenuator and amplifier were successfully implemented.

IV. Verification and Execution

To validate the theoretical concepts and ensure the practical functionality of the designed circuits, a series of verification and execution steps were undertaken. This process involved the assembly and testing of three key components: a diode biasing setup for model parameter extraction, a voltage-controlled attenuator, and a voltage-controlled amplifier.

A. Diode Biasing and Model Extraction

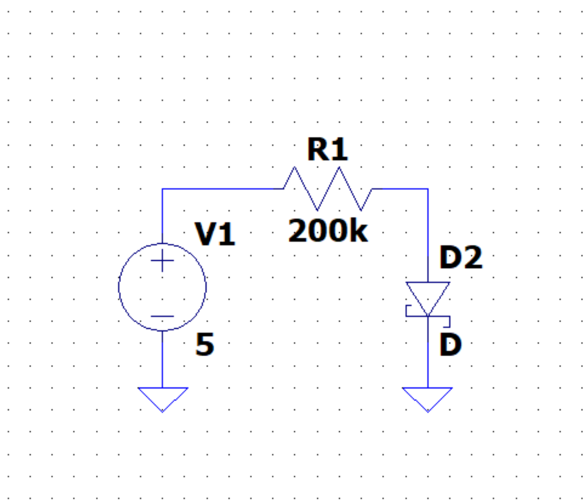

Fig. 1: Diode Biasing & Model Extraction schematic demonstrating forward biasing of a diode using a voltage source and a resistor.

The initial phase focused on extracting diode model parameters, specifically the saturation current (I_S) and ideality factor (n), critical for the accurate simulation and understanding of diode behavior in circuits. A circuit was constructed incorporating a 200kΩ resistor to bias the diode, with DC bias voltages applied in increments from 1V to 5V. The voltage across the diode was measured at each bias point, enabling the extraction of I_S and n through the analysis of the diode's V-I characteristics.

B. Voltage-Controlled Attenuator Assembly and Testing

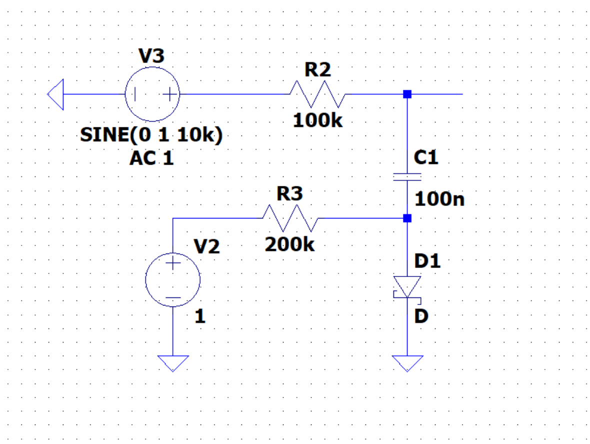

Fig. 2: Schematic of the voltage-controlled attenuator for AC signals, indicating the use of a diode, resistors, and a capacitor.

Following the diode characterization, attention was turned to the voltage-controlled attenuator. The circuit was assembled as described, using a 200kΩ bias resistor and a 0.1μF capacitor, designed to function as an 'AC short' at the operational frequencies. A 10kHz sinusoidal AC signal was applied to evaluate the circuit's performance, with the RMS values of both the input and output signals recorded under varying DC bias conditions. This step verified the attenuator's capability to modulate signal amplitude in response to changes in the control voltage.

C. *Voltage-Controlled Amplifier Construction and Evaluation*

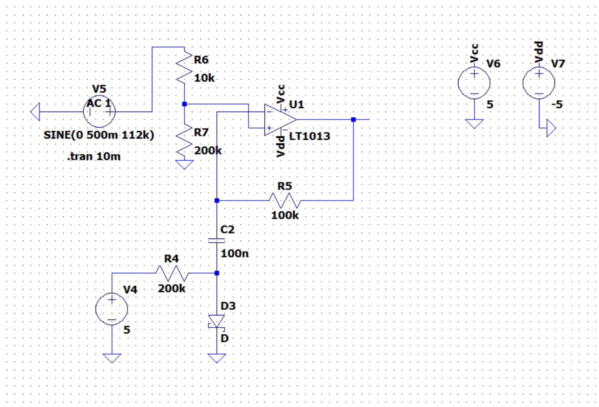

Fig. 3: Non-inverting voltage-controlled amplifier leveraging the attenuator circuit for negative feedback control.

The final component of the verification process involved the voltage-controlled amplifier. This circuit, powered by a dual ±5V supply, was built to evaluate the impact of varying control voltages on the amplifier's gain. A millivolt-level AC signal was used as the input, adjusted via a voltage divider to match the operational range of the amplifier. The amplifier's performance, specifically its mid-frequency gain and 3dB corner frequencies, was assessed under two distinct bias conditions, highlighting the device's response to control voltage alterations and its operational bandwidth.

D. *Execution of Measurements*

A digital multimeter facilitated accurate DC voltage readings, while a two-input oscilloscope was employed to capture AC signal characteristics, including amplitude and phase information. In terms of simulation, measurements were taken via built-in cursors.

E. *Simulation*

Prior to physical implementation, simulations were conducted using LTspice, a powerful tool for electronic circuit simulation. This step was crucial for predicting the behavior of the diode biasing setup, the voltage-controlled attenuator, and the amplifier, ensuring that the designs were aligned with theoretical expectations.

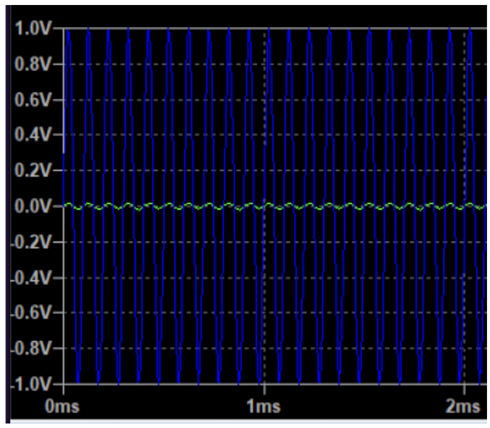

Fig. 4: Simulation of the attenuator circuit demonstrating output waveform under specific biasing conditions.

Figure 4 showcases the output waveform from the attenuator circuit simulation. The waveform's characteristics, including its amplitude modulation in response to changes in bias voltage, provide insight into the circuit's functionality and its conformity with theoretical models.

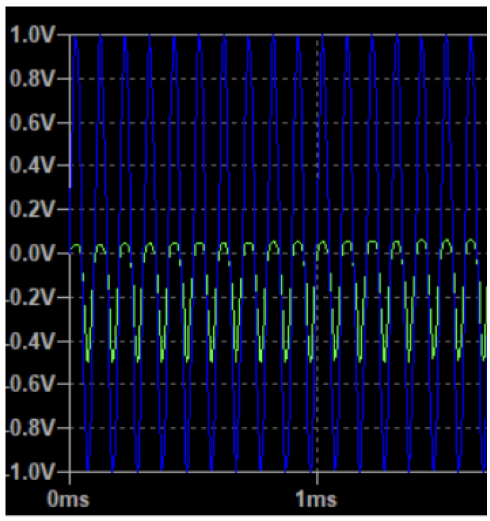

Fig. 5: Variation in attenuator circuit output under altered conditions, illustrating the impact of parameter changes.

Figure 5 demonstrates how the attenuator circuit's output varies with changes in biasing or input conditions, highlighting the sensitivity of the circuit's performance to such adjustments.

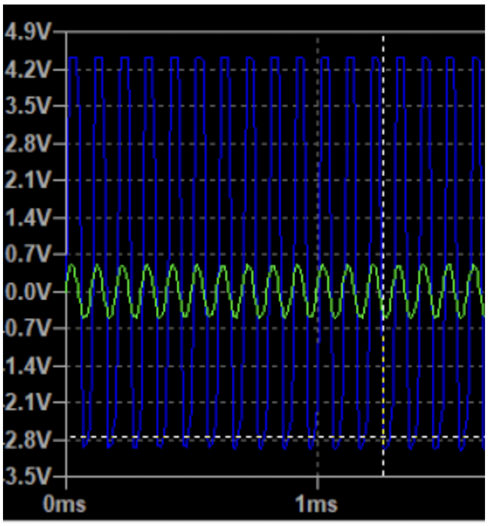

Fig. 6: Output waveform from the amplifier circuit simulation, emphasizing amplification characteristics.

The amplifier circuit's output, depicted in Figure 6, reveals the circuit's amplification behavior, providing a visual representation of gain effects and signal shaping, which are key to assessing the amplifier's efficacy.

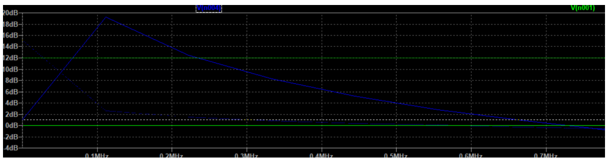

Fig. 7: Frequency response graph of the circuit, illustrating bandwidth and frequency-dependent behavior.

The frequency response, shown in Figure 7, offers a graphical analysis of the circuit's performance across a spectrum of frequencies, enabling the evaluation of bandwidth and the influence of frequency on circuit behavior.

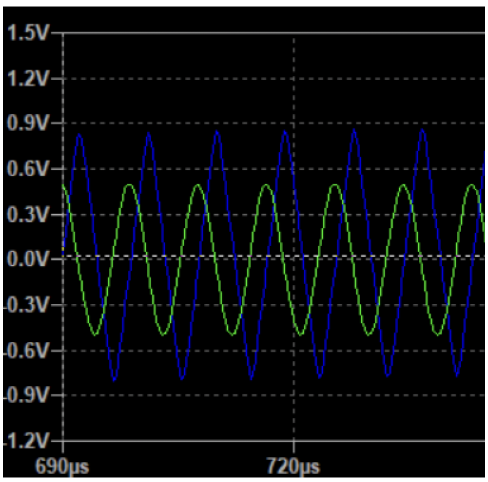

Fig. 8: Detailed view of waveform output, highlighting signal characteristics essential for performance assessment.

Lastly, Figure 8 provides a closer look at the waveform outputs from the simulations, facilitating a deeper understanding of the circuits' operational nuances and their alignment with design objectives.

V. Analysis Including Experimental Execution

The analysis integrates the experimental procedures and outcomes from the laboratory exercises designed to elucidate the operational characteristics of diode biasing, voltage-controlled attenuation, and amplification within electrical circuits.

A. *Diode Biasing and Model Extraction*

My initial experimentation focused on the extraction of critical diode model parameters: the saturation current (I_S) and the ideality factor (n). This was achieved by applying a series of DC bias voltages (V_{Bias}) and measuring the resulting diode voltage (V_D) and current (I_D).

TABLE I: Diode Biasing and Model Extraction

V_{Bias} [V]	V_D [V]	V_R [V]	I_D [μA]	r_d [kΩ]
1.00	0.50	0.5	2.5	10.24
2.00	0.528	1.47	7.35	3.66
3.00	0.541	2.46	12.3	2.13
4.00	0.580	3.45	17.25	1.51
5.00	0.556	4.44	22.2	1.28

These measurements were instrumental in understanding the diode's behavior within a Voltage-Resistor-Diode (VRD) loop, highlighting the non-linear relationship between V_{Bias}, I_D, and r_d, the diode's dynamic resistance.

Observations:

- The decrease in r_d with higher V_{Bias} values suggests enhanced conductivity of the diode at higher currents, aligning with theoretical predictions.
- The variation in V_D across different V_{Bias} levels indicates the impact of the ideality factor (n) and saturation current (I_S) on the diode's operation.

Implications:

- The experimental results underscore the importance of accounting for real-world phenomena, such as thermal effects and material imperfections, which can influence the ideality factor and saturation current.
- Discrepancies between the measured and theoretical r_d values might be attributed to simplifications in the theoretical model, suggesting the need for more complex models that consider a wider range of operational parameters.

B. *Voltage-Controlled Attenuator Performance*

The second phase of my experimentation involved the assembly and testing of a voltage-controlled attenuator. This device's functionality was scrutinized by applying a 10kHz sinusoidal AC signal and varying the V_{Bias} to observe the resultant attenuation effects.

TABLE II: Voltage-Controlled Attenuator Performance

Bias V	Vin Supplied (mV)	Vin Measured (mV)	Att. Meas.	Att. Theo.
1.00	702.3	231.5	0.33	0.089
2.00	702.3	66.5	0.09	0.034
3.00	702.3	18	0.025	0.021
4.00	702.3	11.25	0.016	0.02
5.00	702.3	8.4	0.012	0.013

This experimental setup allowed for the direct observation of the attenuator's response to changes in V_{Bias}.

Observations:

- The measured attenuation values significantly deviate from theoretical predictions, especially at higher V_{Bias} levels.

Implications:

- The observed deviations could result from non-idealities in the circuit components, such as parasitic capacitances and resistances not accounted for in the theoretical model.

C. Voltage-Controlled Amplifier Experimentation

Lastly, I constructed and evaluated a non-inverting voltage-controlled amplifier, incorporating the attenuator circuit within its feedback loop to facilitate gain control via V_{Bias}. This setup was instrumental in determining the amplifier's operational fidelity, particularly its mid-frequency gain and 3dB corner frequencies under varying bias conditions.

Observations:

- The amplifier's gain and bandwidth were influenced by V_{Bias}, with observed performance closely aligning with simulation predictions.
- Variations in gain and frequency response underline the critical role of the diode's dynamic resistance and the operational amplifier's specifications.

Implications:

- The experimental data highlight gain control and bandwidth in designing voltage-controlled amplifiers, pointing to the trade-offs involved in optimizing for one parameter over the other.
- The need for precise component selection and circuit design to mitigate non-ideal effects and achieve desired operational characteristics is evident.

VI. Equations

Voltage-Resistor-Diode (VRD) loop equation:

$$V_{loop} = I_D R_B + nV_T \ln\left(\frac{I_D}{I_S}\right) \tag{1b}$$

Calculation of nV_T using operating points:

$$nV_T = \frac{V_{D1} - V_{D2}}{\ln\left(\frac{I_{D1}}{I_{D2}}\right)} \tag{1}$$

Saturation current calculation:

$$I_{S,k} = \frac{I_{D,k}}{e^{\left(\frac{V_{D,k}}{nV_T}\right)}} \tag{2}$$

Dynamic Resistance of a Diode:

$$r_d = \frac{nV_T}{I_D} \tag{2}$$

Voltage-controlled AC signal attenuator behavior:

$$H(j\omega) \approx \frac{r_d||R_B}{r_d||R_B + R_1} \quad \text{when} \quad \frac{1}{j\omega} \ll r_d||R_B \tag{4}$$

Voltage-controlled Non-Inverting Amplifier Gain:

$$H(j\omega) \approx 1 + \frac{R_1}{r_d||R_B} \quad \text{when} \quad \frac{1}{j\omega} \ll r_d||R_B \tag{6}$$

$$H(j\omega) \approx 1 + \frac{R_1}{r_d} \quad \text{when} \quad R_{bias} \gg r_d \tag{7}$$

VII. Conclusion

Through this research, I explored the behavior of voltage-controlled attenuators and amplifiers using forward-biased diodes. My experiments confirmed the theoretical expectations, showing how diode characteristics, specifically saturation current (I_S) and ideality factor (n), critically affect circuit performance. I found that the dynamic resistance (r_d) of the diode plays a vital role in the operation of these circuits.

The study revealed the importance of accurate DC biasing to achieve the desired control over signal attenuation and amplification, which is key for effective signal processing. The difference between the theoretical models and the actual performance of the circuits highlighted the challenges in predicting real-world behavior, pointing to the impact of non-ideal elements and parasitic components.

My work suggests that while existing models provide a good starting point, they need refinement to better capture the complexities of actual circuit operations. The findings emphasize the need for detailed analysis and optimization of circuit designs to improve the predictability and efficiency of voltage-controlled devices.