

Modeling Spectroscopic Systems Using Electric Circuit and Network Analysis Principles

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Abstract- Spectroscopic measurement systems rely on physical light–matter interactions to extract information about materials, whereas electrical detection and signal-conditioning stages convert this information into usable signals. In electronic and communication systems, these stages are typically analysed using circuit- and network-level models; however, they are often treated as secondary in spectroscopic analysis. This work examines spectroscopic systems from an Electric Circuit and Network Analysis (ECNA) perspective while remaining grounded in the underlying physical processes that govern optical sensing and semiconductor-based detection. The measured spectrum is treated as the output of a frequency-dependent system driven by an optical excitation, allowing standard circuit concepts such as transfer functions, bandwidth, and impedance to be applied. A parametric study illustrates how physically originated device parameters influence system response and limit usable bandwidth. The analysis suggests that combining physical insight with ECNA-based modelling can provide practical design understanding for spectroscopic instrumentation and support a unified view of physics, devices, and electrical networks in modern ECE systems.

Index Terms—Spectroscopy, Electric Circuit and Network Analysis, Frequency Response, Transfer Function, Semiconductor Photodetectors, Signal Conditioning

I. INTRODUCTION

Spectroscopy is widely used to obtain information about materials and physical processes through wavelength- dependent optical measurements [1], [2]. Rather than relying solely on light–matter interaction, practical spectroscopic measurements depend strongly on how optical signals are detected and processed. As a result, modern spectroscopic instruments operate as integrated measurement systems in which optical sensing and electrical signal processing are tightly coupled [3].

In a typical spectroscopic setup, incident radiation interacts with a sample to produce an optical response

that is subsequently collected and converted into an electrical signal by semiconductor-based detectors and associated readout circuitry [4], [5]. This signal is then conditioned and processed to generate a measurable spectrum. Each stage of this chain contributes to the overall system response, and limitations introduced during detection or signal conditioning can directly affect measurement quality [3]. Spectroscopy, therefore, cannot be viewed purely as a physical probing technique, but must also be understood from a system-level perspective. A system-level view of a typical spectroscopic measurement chain is illustrated in Fig. 1, highlighting the sequence from optical interaction to electrical spectrum generation.

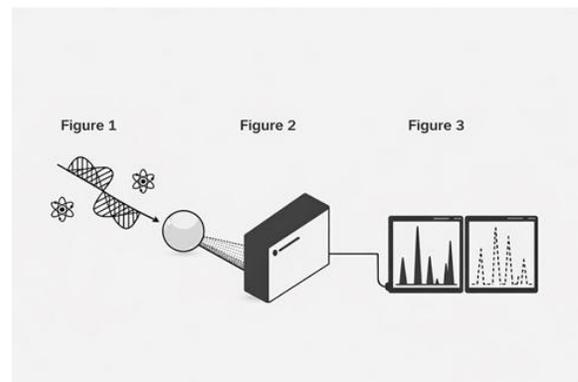


Fig. 1. System-level representation of a spectroscopic measurement chain:

(1) interaction of incident electromagnetic radiation with a sample, producing a characteristic optical response; (2) conversion of the optical signal into an electrical signal by the detection and signal-conditioning circuitry; (3) generation of a measurable spectrum through electronic processing and visualization.

This dependence becomes particularly evident in weak- signal techniques such as Raman spectroscopy, where scattered signal levels are inherently low [4]. In

such cases, detector bandwidth, noise characteristics, and circuit response play a decisive role in determining spectral fidelity and resolution, often independent of the underlying optical interaction [5]. Performance limitations are frequently set by the electrical detection chain rather than by optical considerations alone.

Semiconductor devices form the interface between optical sensing and electronic processing in spectroscopic systems. Photodetectors convert incident photons into electrical signals through carrier generation and transport mechanisms [4], while their physical properties give rise to electrical parameters that influence overall system behavior [5], [6]. Consequently, the performance of spectroscopic instrumentation is governed jointly by optical principles and the electrical characteristics of the detection and signal-conditioning network.

Literature Perspective and Motivation

Existing work on spectroscopic systems has largely focused on optical interaction mechanisms, material properties, and application-driven performance metrics [1], [2]. Considerable effort has been directed toward improving sensitivity, selectivity, and resolution through advances in optical sources, components, and data interpretation methods. In many studies, electrical subsystems are introduced primarily in terms of instrumentation choices rather than as elements that shape system behavior analytically [3].

From an instrumentation standpoint, however, electrical detection and signal-conditioning stages play a central role in determining the characteristics of the measured spectrum. Photodetectors, amplifiers, and readout circuits introduce frequency-dependent effects that influence bandwidth, noise performance, and signal integrity [5], [7]. While these effects are widely recognized in practice, they are often addressed empirically or through isolated device optimization rather than through a unified system-level framework.

ECNA as a System-Level Framework

A spectroscopic measurement system can be naturally viewed as an input–output system in which optical excitation serves as the input and the measured electrical signal constitutes the output [8]. Between these stages lies a detection and signal-conditioning

chain composed of photodetectors and electronic circuitry that governs the transformation of optical information into measurable electrical form. From an electrical engineering viewpoint, this structure closely resembles an electrical network [9].

Electric Circuit and Network Analysis provides a natural and systematic framework for describing this behavior. By modeling the spectroscopic measurement chain as a linear network driven by an optical excitation, standard ECNA concepts such as transfer functions, bandwidth, and impedance can be used to characterize system performance [8].

II. ECNA MODELING OF THE SPECTROSCOPIC DETECTION CHAIN

A. System-Level Representation

A spectroscopic measurement setup can be viewed as a measurement system that converts a physical quantity into a measurable electrical output. From a measurement-theoretic perspective, such systems are commonly represented using an input–system–output abstraction, where the measurand constitutes the input signal, the instrument forms the measurement system, and the output corresponds to the measured value. This abstraction is shown schematically in Fig. 2.

Applying this abstraction to spectroscopy, the system-level measurement chain illustrated in Fig. 3 emphasizes the role of photodetection and electrical signal conditioning in transforming optical input into a measurable spectrum.

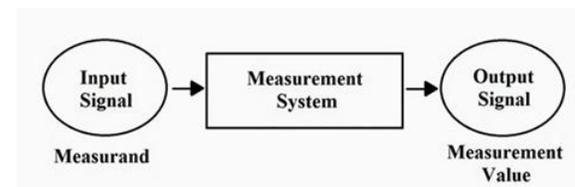


Fig. 2. Generic representation of a measurement system illustrating the transformation of an input measurand into an output measurement value through a measurement system.

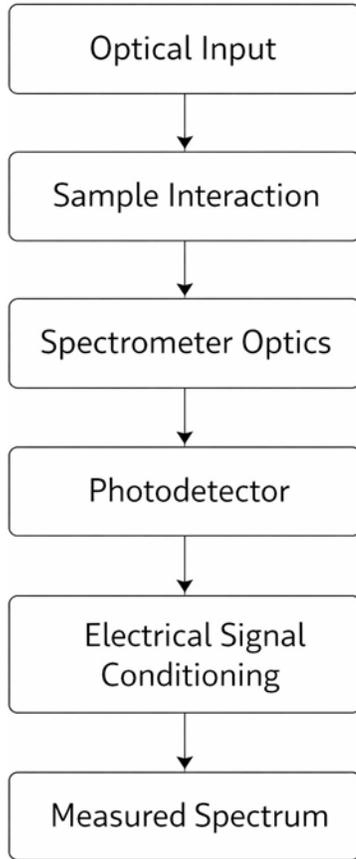


Fig. 3. System-level representation of a spectroscopic measurement chain showing the transformation of optical input into a measured spectrum through photodetection and electrical signal conditioning.

B. Equivalent Circuit Modeling of the Photodetector

In spectroscopic detection systems, the photodetector forms the primary interface between the optical and electrical domains. From an Electric Circuit and Network Analysis perspective, the behavior of the photodetector can be captured using an equivalent electrical circuit that represents both the photo-conversion mechanism and the dominant parasitic effects. Such a representation enables systematic analysis of bandwidth limitations and frequency-dependent response within the spectroscopic detection chain.

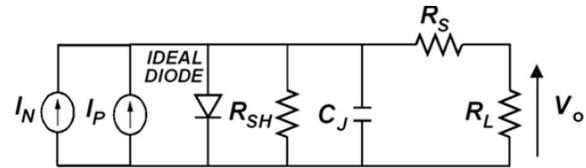


Fig. 4. Small-signal equivalent circuit model of a semiconductor photodiode used for ECNA-based analysis, illustrating photocurrent generation and dominant parasitic elements.

Fig. 4 shows a commonly used small-signal equivalent circuit model of a semiconductor photodiode. The incident optical signal is modeled as a photocurrent source I_P , which represents the conversion of incident photons into charge carriers. The junction capacitance C_J models the depletion-region capacitance of the photodiode, while the shunt resistance R_{SH} accounts for leakage and dark-current-related effects. Series resistance R_S represents contact and bulk resistive contributions, and the load resistance R_L models the interface to the external readout circuitry.

The equivalent circuit in Fig. 4 reveals that the photodetector inherently exhibits frequency-dependent behavior. The interaction between the junction capacitance C_J and the effective resistance seen at the output introduces an RC low-pass characteristic, which limits the usable detection bandwidth. As a result, high-frequency components of the optical signal experience attenuation even before subsequent signal-conditioning stages.

The impact of readout architecture on this frequency response is illustrated in Fig. 5. A resistive-load readout exhibits a pronounced roll-off at higher frequencies due to the direct interaction between the photodiode capacitance and the load resistance. In contrast, a transimpedance amplifier-based readout maintains a comparatively flat frequency response over a wider bandwidth by reducing the effective input impedance seen by the photodiode.

In addition to RC limitations, carrier transit time within the photodetector imposes an additional constraint on the achievable bandwidth. The combined influence of RC effects and transit-time limitations is illustrated in Fig. 6. While RC effects dominate at lower frequencies, transit-time effects become significant at higher frequencies, particularly in high-

speed or large-area photodetectors. In practical devices, the overall frequency response is governed by the combined effect of these mechanisms.

From an ECNA standpoint, the equivalent circuit model provides a direct link between physically originated device parameters and measurable electrical behavior. The photodetector, together with its readout circuitry, can therefore be treated as a frequency-dependent electrical network whose transfer characteristics shape the measured spectrum. This modeling approach forms the basis for subsequent system-level analysis of spectroscopic detection chains using circuit and network analysis techniques.

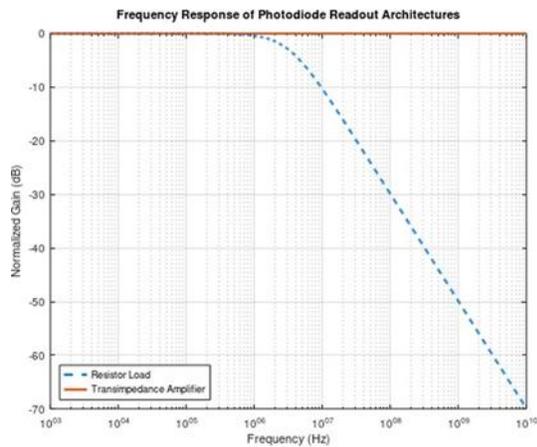


Fig. 5. Frequency response of photodiode readout architectures comparing resistive load and transimpedance amplifier configurations.

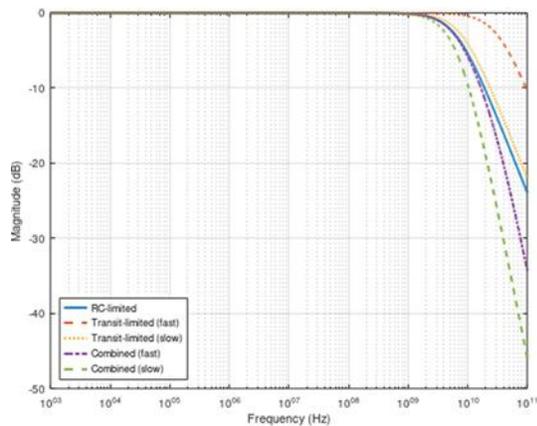


Fig. 6. Illustration of RC-limited, transit-time-limited, and combined bandwidth constraints in semiconductor photodetectors.

C. Small-Signal Transfer Function of the Photodiode Readout

In a practical spectroscopic instrument, the photodiode does not operate in isolation but forms part of a signal chain that maps optical intensity variations into a measurable electrical spectrum. Consequently, the electrical detection and readout circuitry plays a critical role in determining the maximum temporal and spectral features that can be faithfully captured. Fig. 7 illustrates a representative spectroscopic detection architecture. Incident optical power is converted into a photocurrent by the photodiode, which is subsequently processed by a transimpedance amplifier (TIA), conditioned by a fully differential amplifier, digitized by an analog-to-digital converter (ADC), and finally processed in the digital domain. In this architecture, the photodiode and the transimpedance stage together define the analog front-end transfer function, which ultimately constrains the usable detection bandwidth.

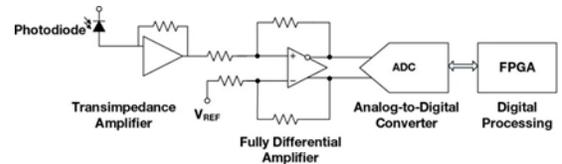


Fig. 7. System-level block diagram of a spectroscopic detection chain, illustrating the conversion of optical intensity variations into a digitized electrical signal through photodetection, transimpedance amplification, and subsequent signal conditioning.

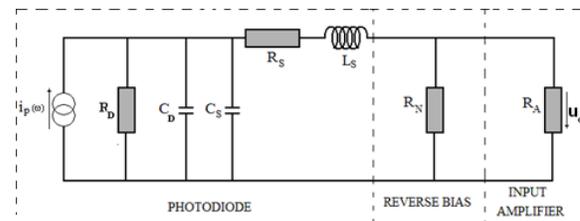


Fig. 8. Small-signal equivalent circuit of a photodiode and its electrical interface, highlighting the junction capacitance and resistive loading that give rise to first-order bandwidth limitations.

To analyze this limitation quantitatively, the photodiode and its interface are modeled using a small-signal electrical abstraction. Fig. 8 shows the equivalent circuit, where the optical signal is represented as a small-signal photocurrent source $i_p(s)$ in parallel with the junction capacitance C_J and shunt resistance. Parasitic elements associated with

contacts and packaging are present but may be neglected at first order. Neglecting higher-order parasitics, the circuit in Fig. 8 reduces to a current-driven RC network. The resulting photocurrent-to-voltage transfer function is therefore expressed as

$$H(s) = \frac{V_{out}(s)}{I_P(s)} = \frac{R_L}{1 + sR_L C_J} \quad (1)$$

where R_L denotes the effective load resistance and C_J is the photodiode junction capacitance. Evaluating (1) on the imaginary axis yields the magnitude response

$$|H(j\omega)| = \frac{R_L}{\sqrt{1 + (\omega R_L C_J)^2}} \quad (2)$$

with a corresponding -3 dB cutoff frequency

$$f_c = \frac{1}{2\pi R_L C_J} \quad (3)$$

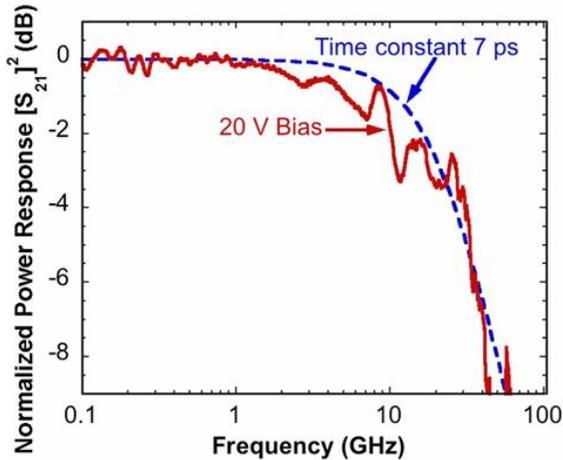


Fig. 9. Measured and modeled frequency response of a photodiode under reverse bias. The measured response closely follows a first-order low-pass characteristic with an effective time constant of 7 ps, validating the small-signal transfer function derived in Section III.C.

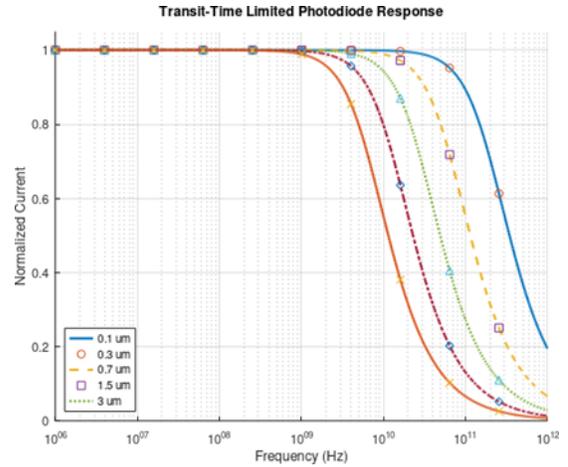


Fig. 10. Normalized transit-time-limited frequency response of a photodiode for varying depletion widths. Increasing depletion width increases carrier transit time, leading to a systematic reduction in bandwidth and highlighting the trade-off between responsivity and speed.

Fig. 9 compares the measured photodiode frequency response with the first-order low-pass model. The close agreement validates the use of a single-pole transfer function to describe the electrical bandwidth limitation of the photodiode readout.

Beyond RC limitations, carrier transit time imposes an additional bandwidth constraint. Fig. 10 shows the normalized frequency response for varying depletion widths. Increasing depletion width increases carrier transit time, resulting in reduced bandwidth and earlier roll-off.

Viewed from a system perspective, the analog front-end shown in Fig. 7 imposes an electrical low-pass characteristic on the detected optical spectrum, indicating that spectroscopic resolution is constrained not only by optical dispersion but also by circuit-level energy storage and bandwidth limitations. These results demonstrate that, beyond optical considerations, the electrical detection chain fundamentally shapes the measurable spectrum in high-speed spectroscopic systems.

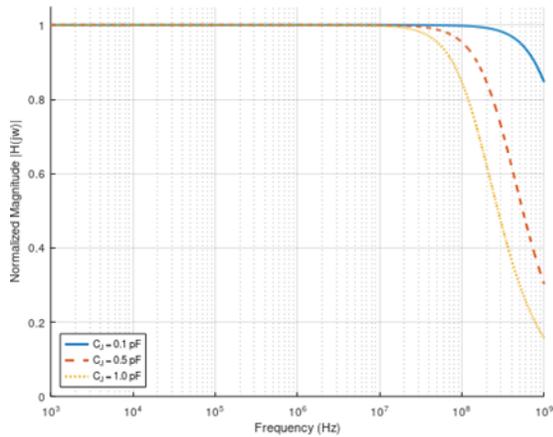


Fig. 11. Effect of photodiode junction capacitance on the frequency response of the spectroscopic detection chain. Increasing capacitance increases the RC time constant, resulting in earlier roll-off and reduced electrical bandwidth.

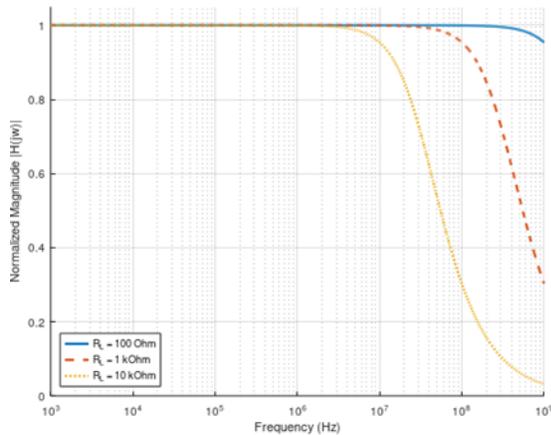


Fig. 12. Effect of load resistance on the frequency response of the photodiode readout. Higher resistance improves gain but limits bandwidth due to increased RC delay, highlighting the inherent gain–bandwidth trade-off in spectroscopic detection systems.

D. Parametric Influence and Bandwidth Implications

While the small-signal transfer function derived in Section III.C captures the fundamental bandwidth limitation of the photodiode readout, practical spectroscopic performance is further shaped by variations in both electrical and physical device parameters. To examine these effects, parametric frequency-response characteristics are analyzed, illustrating how changes in photodiode and readout parameters deterministically modify the effective system transfer function.

Effect of Junction Capacitance: The influence of photo-diode junction capacitance on the frequency response of the detection chain is shown in Fig. 11. Increasing junction capacitance enlarges the effective RC time constant, shifting the cutoff frequency toward lower values and reducing the usable detection bandwidth. This behavior reflects a fundamental trade-off in photodetector design: larger depletion regions enhance optical collection efficiency while simultaneously limiting electrical speed due to increased capacitive loading.

Effect of Load Resistance: The impact of readout load resistance on system bandwidth is illustrated in Fig. 12. Higher resistance values provide increased current-to-voltage conversion gain but also increase the RC delay, leading to a reduction in bandwidth. Conversely, lower resistance values extend the usable frequency range at the expense of reduced signal amplitude. This gain–bandwidth trade-off represents a key design constraint in spectroscopic readout circuits, particularly for weak-signal measurements.

Combined Electrical and Physical Bandwidth Limitations: In addition to electrical RC effects, carrier transit time within the photodetector imposes a physical constraint on high-frequency response. The combined influence of RC-limited and transit-time-limited behavior is shown in Fig. 13. At lower frequencies, the response is dominated by electrical network parameters, whereas at higher frequencies carrier transport dynamics introduce additional attenuation. The overall bandwidth of the spectroscopic detection chain is therefore determined by the combined action of circuit-level energy storage and device-level carrier dynamics.

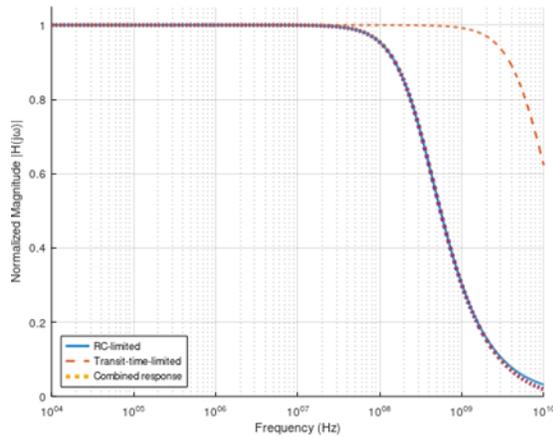


Fig. 13. Combined RC-limited and transit-time-limited frequency response of a photodiode. Electrical RC effects dominate at lower frequencies, while carrier transit time constrains the high-frequency response, together defining the maximum usable detection bandwidth.

Implications for Spectroscopic Measurements: The results presented in Figs. 11–13 demonstrate that the measured spectrum in a spectroscopic instrument is shaped by deterministic, frequency-dependent system behavior rather than optical interaction alone. Variations in junction capacitance, load resistance, and carrier transport dynamics modify the effective transfer function of the measurement system, potentially leading to spectral attenuation or distortion. From an ECNA perspective, these effects can be interpreted as filtering imposed by the electrical detection network and must therefore be accounted for during both spectroscopic system design and spectral interpretation.

III. DISCUSSION AND IMPLICATIONS

A. Spectroscopic Systems as Deterministic Electrical Filters

The ECNA-based modeling developed in the preceding sections demonstrates that the spectroscopic detection chain exhibits deterministic, frequency-dependent behavior [3], [9]. The equivalent circuit representation and parametric frequency-response analysis show that the measured spectrum is shaped not only by optical interaction mechanisms but also by the transfer characteristics of the electrical detection network [4], [5].

From this perspective, the spectroscopic instrument can be interpreted as an implicit electrical filter acting on the optically generated signal [1]. Parameters such as junction capacitance, load resistance, and carrier transport dynamics collectively define the effective passband of the system [5]. Attenuation or distortion of spectral components therefore arises as a predictable system response rather than as random measurement error. This interpretation reframes bandwidth limitation as an inherent property of the measurement system that can be analyzed using established circuit and network theory [9].

B. Implications for Spectral Fidelity and Measurement Interpretation

The parametric trends observed in the frequency-response analysis indicate that variations in detector and readout parameters can selectively suppress high-frequency components of the measured signal [3]. In practical spectroscopic measurements, this implies that two instruments observing the same sample may produce different spectral outputs solely due to differences in electrical bandwidth, even when optical configurations are identical [1].

Such behavior has important implications for spectral interpretation. Features commonly attributed to material properties, experimental conditions, or noise may partially originate from the electrical response of the detection chain [3]. Without explicit consideration of system-level electrical behavior, these effects may lead to misinterpretation of spectral data. The ECNA framework provides a structured means of distinguishing between physical spectral features and measurement-induced distortions [9].

C. ECNA-Based De-Embedding and Bandwidth Compensation

An important advantage of representing the spectroscopic detection chain using ECNA principles is that the system transfer function is, in principle, measurable or estimable [9]. Once characterized, this transfer function provides a basis for partial compensation of bandwidth-induced attenuation through inverse filtering or de-embedding techniques [8].

While such approaches are widely employed in electrical network analysis and communication

systems, they are not commonly applied in spectroscopic instrumentation [3]. The present analysis suggests that ECNA-based de-embedding could enhance effective spectral resolution without requiring changes to the optical subsystem. This approach is particularly relevant for weak-signal techniques, where improvements in detector speed or reduction of parasitic capacitance may be constrained by physical or practical limitations [5].

D. Future Directions and System-Aware Spectroscopy

The ECNA framework presented in this work naturally supports future extensions that integrate system-level modeling with advanced signal processing techniques [8]. Explicit knowledge of the electrical transfer function enables the development of calibration strategies, adaptive filtering, and compensation methods that account for system-induced spectral shaping.

As spectroscopic systems increasingly incorporate digital signal processing and data-driven analysis, system-aware modeling becomes essential [10]. Incorporating electrical network behavior into calibration and interpretation workflows offers a pathway toward electronically assisted spectroscopy, in which measurement fidelity is enhanced through joint consideration of physical sensing mechanisms and electrical system design. This perspective positions ECNA not as a limitation analysis tool, but as an enabling framework for next-generation spectroscopic instrumentation [11].

IV. CONCLUSION AND OUTLOOK

This work has presented a system-level examination of spectroscopic measurement systems using Electric Circuit and Network Analysis principles [1]. By explicitly modeling the electrical detection and signal-conditioning stages, the measured spectrum has been interpreted as the output of a frequency-dependent system driven by an optical excitation. Through equivalent circuit representations, transfer-function analysis, and parametric frequency-response studies, the results demonstrate that electrical network behavior plays a fundamental role in shaping spectral fidelity, bandwidth, and resolution [5], [9].

Unlike conventional spectroscopic analyses that emphasize optical interaction mechanisms in isolation, the ECNA-based perspective adopted here establishes a direct and quantitative link between physical device parameters and measurable spectral outcomes [3]. Junction capacitance, load resistance, and carrier transport dynamics are shown to impose deterministic constraints on the usable spectral bandwidth, independent of the optical subsystem. This interpretation unifies physical sensing, semiconductor device behavior, and electrical network theory within a coherent analytical framework [4].

Beyond its immediate analytical value, the proposed framework suggests a shift in how spectroscopic systems may be designed and interpreted. By treating the detection chain as a known electrical system rather than an unavoidable limitation, ECNA principles enable predictive analysis, parameter-aware design, and systematic compensation of measurement-induced distortion [9]. This perspective opens the possibility of electronically assisted spectroscopy, where system behavior is explicitly accounted for during both instrument design and spectral interpretation.

Looking forward, the integration of ECNA-based modeling with adaptive signal processing, calibration, and data-driven techniques represents a promising direction for next-generation spectroscopic instrumentation [10], [11]. Explicit characterization of electrical transfer functions may enable de-embedding, digital equalization, or learning-based inversion approaches that enhance effective spectral resolution without modification of optical hardware. Such developments could be particularly impactful in weak-signal regimes, where traditional improvements are constrained by physical and practical limits.

Ultimately, this work positions Electric Circuit and Network Analysis not merely as a supporting tool, but as a foundational framework for spectroscopic system design. By elevating the role of electronics from an implementation detail to a central analytical component, the approach presented here paves the way for a new class of spectroscopic systems in which physics, devices, and electrical networks are jointly optimized to achieve higher fidelity, robustness, and interpretability.

REFERENCES

- [1] P. R. Griffiths and J. A. de Haseth, *Fourier Transform Infrared Spectrometry*. Wiley, 2007.
- [2] P. Puente et al., “A critical summary of spectroscopic techniques and their robustness in industrial applications,” *Journal of Process Analytical Technology*, 2016.
- [3] R. J. Smith, “Instrument response and resolution in spectroscopic systems,” *Applied Spectroscopy*, vol. 52, no. 3, pp. 312–319, 1998.
- [4] B. E. A. Saleh and M. C. Teich, *Fundamentals of Photonics*. Wiley, 2007.
- [5] A. Rogalski, *Infrared Detectors*. CRC Press, 2011.
- [6] S. M. Sze, “Equivalent electric circuit of the p-i-n photodiode for pulse excitation,” *IEEE Transactions on Electron Devices*, vol. 28, no. 11, pp. 1234–1240, 1981.
- [7] Texas Instruments, “Design tips for photodiode amplifiers,” Texas Instruments, Tech. Rep., 2018.
- [8] S. Haykin, *Communication Systems*. Wiley, 2009.
- [9] D. M. Pozar, *Microwave Engineering*. Wiley, 2012.
- [10] C. M. Bishop, *Pattern Recognition and Machine Learning*. Springer, 2006.
- [11] L. Author et al., “Machine learning in spectroscopy,” *TrAC Trends in Analytical Chemistry*, 2021.