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Viewpoint

Understanding and Equivalence of Response Time Measurements in Photodetectors

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ABSTRACT: The response time of a photodetector is a key figure of merit that determines its ability to follow rapid variations in optical intensity, impacting applications from high-speed communication and time-of-flight ranging to ultrafast imaging and time-resolved spectroscopy. Yet reported response times often differ widely because commonly used measurement techniques probe fundamentally distinct physical processes. This Viewpoint systematically analyzes three widely used measurement techniques—the square-pulse response, the ultrafast-pulse transient response, and the 3 dB bandwidth method—and clarifies the specific detector dynamics each technique measures. We identify the conditions under which these methods are formally equivalent and the regimes where their results necessarily diverge. In particular, we emphasize that the detector response time is not an intrinsic material constant but rather a quantity that depends on the device operating conditions, including excitation intensity, carrier density, and device operating regime. By establishing a unified framework linking time- and frequency-domain characterizations, this work clarifies long-standing confusion surrounding response-time reporting and provides practical guidance for selecting appropriate measurement strategies across diverse photonic and optoelectronic applications.

1. INTRODUCTION

The response time of a photodetector determines its ability to track rapid variations in optical intensity and therefore plays a central role in applications such as optical communication, ultrafast imaging, time-of-flight (ToF) ranging, and time-resolved spectroscopy.[1−4] Although the term "response time" is widely used, its physical meaning depends strongly on how it is measured, making the metric far less universal than often assumed. In optical telecommunications and interconnect systems, detector speed is conventionally defined by the 3 dB bandwidth, which captures the small-signal frequency response that ultimately limits high-speed data transmission. By contrast, optoelectronic device characterization commonly employs ultrafast-pulse transient measurements and square-pulse tests, which probe the time-domain response and can more directly expose carrier-transport and recombination dynamics, as well as system-level RC limitations, particularly under large-signal or nonlinear operating conditions. Since these techniques interrogate different physical processes, the "response time" extracted from each method is not inherently equivalent and should not be compared directly unless the underlying physical assumptions are satisfied. A meaningful assessment of detector performance therefore requires a clear comparison across measurement approaches, enabling a consistent interpretation of device speed and providing a unified benchmark for evaluating technological progress in the field.

However, these three measurement techniques are frequently treated as interchangeable, often with the implicit assumption that they yield equivalent results. In practice, such equivalence holds only under linear time-invariant (LTI) conditions—an assumption that is easily violated yet seldom verified—resulting in inconsistent and sometimes misleading interpretations of detector performance.[5,6] Consequently, reported response times for nominally similar photodetectors can differ by orders of magnitude—often solely due to the choice of measurement technique—creating ambiguity and hindering meaningful cross-comparison across research communities.[6−8] For example, solution-processed perovskite photodetectors have been reported with small-signal 3 dB bandwidths approaching ∼3 MHz, while time-domain transient photocurrent measurements on comparable devices reveal rise and decay dynamics in the ∼0.18−0.6 μs range.[9] A related discrepancy is observed in photoresponsive perovskite diodes, where small-signal frequency-response measurements yield 3 dB bandwidths of ∼22 MHz, whereas square-pulse or time-resolved electroluminescence measurements exhibit millisecond-scale decay dynamics.[8] Such apparent discrepancies reflect fundamentally different operating regimes and physical processes probed by frequency- and time-domain techniques, rather than inconsistencies in device performance. The absence of a unified framework that connects and differentiates these measurement approaches further obscures the true physical limits governing detector speed. This viewpoint seeks to elucidate the physical meaning underlying each technique, to delineate the conditions under which the methods are equivalent or diverge, and to provide practical guidance for selecting an appropriate characterization strategy based on the operating regime and targeted application.

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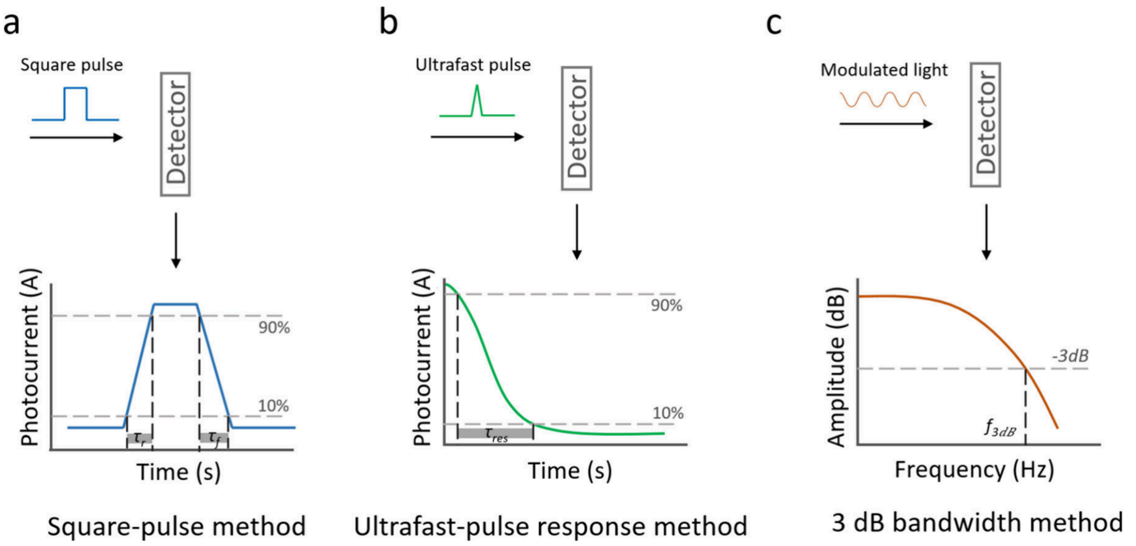

Square-pulse method Ultrafast-pulse response method 3 dB bandwidth method

Figure 1. Schematic diagram of response-time measurement techniques for photodetectors. (a) Square-pulse method: rise and fall times are extracted from the 10–90% transitions of the step response. (b) Ultrafast-pulse response method: a short optical pulse and the transient photocurrent yield the detector's impulse response. (c) 3 dB bandwidth method: under small-signal sinusoidal modulation, the −3 dB cutoff frequency defines the small-signal bandwidth.

2. RESPONSE TIME MEASUREMENT METHODS

2.1. Square-Pulse Method

In this method (Figure 1a), a step-like optical signal (often implemented experimentally using a square-wave modulation) is applied to the detector, and the temporal evolution of the electrical output is recorded.[5,10,11] The response time (τ_{res}) is typically defined as the 10–90% rise or fall interval of the steady-state signal, quantifying how rapidly the device follows an abrupt change in illumination. The transient waveform generally contains two characteristic times: the rise time (τ_{r}) during the light-on transition and the fall time (τ_{f}) during the light-off transition. The rise time is governed by carrier generation, drift, diffusion, and circuit charging, whereas the fall time reflects carrier recombination, trap release, and circuit discharging. In an ideal linear system, these two times are nearly symmetric ($\tau_{\mathrm{r}} \approx \tau_{\mathrm{f}}$), indicating comparable rates for carrier transport and recombination. However, in many practical photodetectors—particularly those based on low-mobility or trap-rich materials such as halide perovskites, colloidal quantum dots, and metal oxides—the fall time can exceed the rise time by orders of magnitude due to slow carrier release, trapped-charge dynamics, and persistent photoconductivity.[7,12] The response time extracted from square-pulse measurements therefore reflects the slowest process in the overall system, whether dominated by the external RC time constant or by the intrinsic carrier transport and recombination dynamics. For this reason, square-pulse tests remain widely used for system-level characterization of optoelectronic devices, whereas ultrafast-pulse methods are preferred when resolving intrinsic, material-limited carrier dynamics, as discussed in the following section.

2.2. Ultrafast-Pulse Response Method

In the ultrafast-pulse response method (Figure 1b), a short optical pulse with a duration much shorter than the detector's intrinsic response time serves approximately as a δ-function excitation.[13,14] The resulting transient photocurrent approximates the detector's impulse response, convolved with the bandwidth of the measurement circuitry, providing insight into carrier generation, drift, diffusion, and recombination processes. In practice, the measured waveform often exhibits a rapid initial rise followed by a slower decay. Accordingly, the response time is conventionally defined as the 10–90% decay interval of the normalized transient, which offers a consistent and comparable measure across experiments and excitation conditions, even when slower carrier dynamics extend well beyond the peak. To gain further physical insight, the decay portion of the waveform can be fitted with single- or multiexponential functions, yielding characteristic time constants, often described in terms of a fast component (τ_{fast}) and a slow component (τ_{slow}), along with their relative amplitudes. These parameters reveal the underlying transport and recombination processes—where τ_{fast} typically reflects carrier drift and circuit-limited response, while τ_{slow} captures slower mechanisms such as carrier trapping, diffusion, or space-charge relaxation. Together, the 10–90% fall time and the extracted exponential components provide a comprehensive description of both the effective detector speed and the underlying carrier dynamics. This approach offers the highest temporal resolution and is invaluable for probing the intrinsic speed limits of photodetectors. The excitation pulse may range from femtoseconds to nanoseconds, as long as it remains significantly shorter than the system response time. Accurate interpretation, however, requires careful control of the optical fluence to avoid nonlinear phenomena such as saturation, space-charge screening, or field-dependent transport, since the transient shape is highly fluence-dependent once nonlinear effects emerge. Additionally, the electrical bandwidth of the readout circuit (e.g., oscilloscope, cabling) must be sufficient to resolve the transient features; otherwise, bandwidth limitations broaden the measured transient response and obscure fast carrier dynamics.

To distinguish impulsive from step-like excitation, the pulse duration should be compared with the shortest relevant time constant of the device-plus-readout system. When the pulse is much shorter than this time constant, the measured transient approximates an impulse response, with early time dynamics governed by the fastest processes and the decay reflecting the

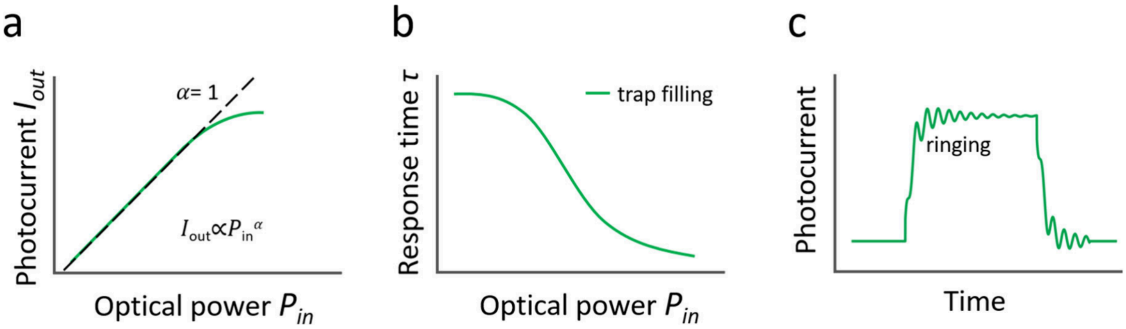

Figure 2. Equivalence conditions and the divergence in response-time measurements. (a) In this linear regime, the detector can be treated as linear time-invariant (LTI), and the time- and frequency-domain descriptions are mathematically equivalent. (b) Operating-point dependence: under trap-filling conditions, the effective response time τ decreases with increasing optical power, i.e., the measured response becomes faster at higher excitation. (c) Ringing caused by impedance mismatch makes the definition of response time inaccurate.

slowest relaxation. In contrast, step-like on/off illumination yields a step response dominated by the longest time constant during both turn-on and turn-off, which are identical in an ideal linear time-invariant system.

2.3. 3 dB Bandwidth Method

The frequency-domain approach characterizes detector speed by applying a small-signal, sinusoidally modulated optical input and measuring the output amplitude as a function of modulation frequency.[15,16] As shown in Figure 1c, the frequency at which the output power decreases by 3 dB from its low-frequency value defines the 3 dB bandwidth f_{3dB}. For an ideal linear, single-pole system, the 10−90% response time τ_{res} is approximately related to the cutoff frequency through the well-known relation $\tau_r \approx 0.35/f_{3dB}$, which follows from the analytic step response of a first-order system.[17] This method is particularly prevalent in characterizing high-speed optical communication systems, photonic integrated circuits, and optoelectronic link characterization, where the small-signal frequency response provides a first-order indicator of the linear modulation bandwidth, while ultimate link performance is typically verified under large-signal operation (e.g., eye diagrams and bit-error-rate measurements). Its principal advantages include high accuracy, excellent reproducibility, and strong immunity to noise, as it relies on steady-state amplitude measurements rather than transient waveforms. The technique is also easily standardized and compatible with network analyzers, making it a practical tool for benchmarking detector bandwidths and verifying circuit performance. However, the 3 dB bandwidth method inherently probes the small-signal electronic response of the detector−amplifier system. It therefore probes the small-signal (linearized) frequency response around a given operating point and may not capture strongly nonlinear or large-signal transient behavior. Consequently, while the 3 dB method provides a robust metric of the small-signal linear bandwidth around a given operating point, it must be interpreted cautiously when comparing with time-domain response times obtained under different excitation regimes and waveform amplitudes.

3. EQUIVALENCE CONDITIONS

The step, impulse, and frequency responses constitute three mathematically equivalent descriptions of a detector's temporal behavior. Specifically, the impulse response is the time derivative of the step response in an LTI system, and the frequency response is the Fourier transform of the impulse response. Under LTI conditions, the square-pulse, ultrafast-pulse, and 3 dB bandwidth methods yield consistent characterizations of the same underlying system response.[5] In this regime, the time- and frequency-domain measurements are connected through the single-pole low-pass relationship $\tau_r \approx 0.35/f_{3dB}$, and the response times extracted from different techniques are directly interchangeable. This equivalence, however, breaks down once the detector departs from linearity or time invariance. Nonlinear phenomena—such as carrier saturation, trap filling, or space-charge screening—introduce a distribution of effective, intensity-dependent time constants, causing the transient response to deviate from a single-exponential form.[18] As a result, frequency-domain bandwidths, which rely on small-signal linearization, no longer correspond to time-domain transient time scales extracted from large-signal waveforms, and often overestimate the apparent detector speed because slow, long-lived tail components contribute weakly to the small-signal frequency response and therefore do not strongly influence the extracted bandwidth. Experimentally, as shown in Figure 2a, linearity can be assessed by examining how the output photocurrent (I_{out}) scales with the incident optical power (P_{in}) through the relation $I_{out} \propto P_{in}{}^{\alpha}$, where $\alpha = 1$ indicates linear operation and deviations from unity signify the onset of nonlinear behavior.[6,19]

4. METHODOLOGICAL AND SYSTEM-LEVEL DIVERGENCE

Even when the intrinsic device physics satisfies the LTI conditions described above, practical measurements can deviate from time−frequency equivalence due to methodological and system-level factors. A central issue is operating-point dependence (Figure 2b). In gain-type photodetectors—such as photoconductors and many quantum-dot or perovskite devices—the effective response time often varies with illumination intensity and bias because trap filling, carrier accumulation, or space-charge effects modify the dominant dynamical processes.[20−23] Under such conditions, the characteristic time constant is not fixed but becomes a function of excitation level, reflecting transitions between trap-limited, transport-limited, and saturation-dominated regimes. Consequently, meaningful comparison among square-pulse, ultrafast-pulse, and frequency-domain (3 dB) measurements requires consistent operating conditions, including illumination intensity, bias, and modulation depth. If these parameters differ, each method may probe a distinct dynamical regime rather than a single intrinsic device property. In such cases, discrepancies among reported response times do not signify failure of theoretical equivalence, but instead reflect the state-dependent nature of detector dynamics.

Beyond intrinsic material nonlinearities, extrinsic circuit factors—most notably impedance mismatch—can also sever the link between time- and frequency-domain results. High-speed measurements typically require a strict 50 Ω environment; impedance discontinuities between the photodetector, cabling, and readout electronics induce signal reflections and ringing artifacts (Figure 2c). These parasitic circuit effects distort the transient pulse shape in time-domain tests and generate passband ripples in frequency-domain characterizations, rendering the theoretical conversion factors (e.g., 0.35) inapplicable even if the detector itself operates linearly.

5. CONCLUSION

This Viewpoint establishes that the "response time" of a photodetector is not an intrinsic material constant, but a measurement-dependent quantity whose physical meaning is determined jointly by the probing technique and the device operating regime. Square-pulse, ultrafast-pulse, and 3 dB bandwidth measurements interrogate fundamentally different aspects of detector behavior—namely, large-signal system-level response governed by device and readout dynamics, early time intrinsic carrier transport and recombination within the device under nonequilibrium excitation, and small-signal linear electronic bandwidth, respectively. These approaches yield mutually consistent response times only when the detector operates as a linear, time-invariant system effectively dominated by a single time constant, for which time- and frequency-domain descriptions are mathematically equivalent. Once nonlinear carrier effects, saturation, trapping, or spatial transport limitations arise, the extracted response times naturally diverge, with each metric reflecting a distinct physical process rather than a single characteristic speed.

A meaningful interpretation of response-time measurements therefore requires explicit identification of the operating regime. Within this framework, three practical guidelines emerge. First, when the detector behaves linearly and the goal is to benchmark small-signal modulation bandwidth, frequency-domain measurements and the 3 dB bandwidth provide a rigorous and well-defined metric. Second, when large-signal behavior, recovery dynamics, hysteresis, or history-dependent effects are relevant, square-pulse measurements offer a more representative characterization of system-level performance under sustained excitation. Third, when probing early time intrinsic carrier dynamics under strongly non-equilibrium conditions, ultrafast-pulse excitation is required to access transport, field screening, and intensity-dependent recombination before slower relaxation processes dominate.

Crucially, meaningful comparison across devices and studies further requires explicit reporting of the operating point, including electrical bias, optical background, and excitation amplitude, together with the specific response-time metric employed (e.g., 3 dB bandwidth, 10−90% transient time, or recovery time). By explicitly linking measurement protocols, operating regimes, and reported time constants, this work provides a unified interpretive framework that reconciles apparently conflicting response-time reports and enables transparent comparison across research communities. This framework establishes a consistent foundation for selecting, interpreting, and reporting photodetector speed in ultrafast detection, optical communication, and time-resolved photonic systems.

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Notes

The authors declare no competing financial interest.

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