

Low SWaP rugged RF photodiode module with application defined MMIC matching circuit

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ABSTRACT

A compact packaged RF photodiode platform with application-specific microwave responses is presented. The proposed architecture integrates an InGaAs/InP photodiode chip with a monolithic microwave integrated circuit (MMIC), enabling different microwave responses by modifying only the MMIC. To demonstrate the concept, three module variants were fabricated: a broadband module with a 3 dB bandwidth exceeding 30 GHz and two narrowband modules operating at approximately 3 GHz and 24 GHz. Experimental characterization confirms stable optical coupling over the investigated temperature range and reproducible RF performance among the fabricated modules. The broadband module further demonstrates high-linearity operation over the investigated temperature range. The proposed platform provides a flexible and manufacturable solution for realizing application-specific microwave photonic receivers, making it suitable for applications including radio-over-fiber links, phased-array antennas, and satellite communication systems.

Keywords: photodiode, photonics payload, microwave, APL, microwave photonics, RoF, MMIC, photonic packaging

1. INTRODUCTION

Photonic-enabled satellite payloads [1] have the potential to improve performance while reducing size, weight, and power (SWaP). Compared with conventional RF electrical interconnects, optical fiber provides greater routing flexibility, lower mass, and inherent immunity to electromagnetic interference (EMI), enabling low-loss transmission of high-frequency signals over long distances. Consequently, compact SWaP-optimized packaged photodiodes [2] are attractive building blocks for very high throughput satellite (VHTS) communication systems [3]. Beyond satellite applications, packaged photodiodes are widely employed in radio-over-fiber (RoF) and analog photonic link (APL) systems, including 5G mobile fronthaul and beyond with remote radio heads (RRHs) [4], indoor distributed antenna systems (DAS) [5], radar systems [6], phased-array antennas for optical beam forming [7], radio astronomy [8], and microwave-photonic frequency synthesis [9] for ultra-low-noise local oscillators [10].

Packaged RF photodiodes often incorporate resistive matching networks to achieve operation over a wide microwave frequency range. In this approach, broadband impedance matching is achieved at the expense of dissipative loss, which limits the achievable O/E conversion gain. In contrast, reactive matching networks can provide frequency-selective impedance matching with reduced dissipative loss [11]. Such application-specific matching networks can become increasingly complex when implemented using discrete components, where component placement and interconnections introduce additional parasitics and manufacturing variability.

Monolithic microwave integrated circuits (MMICs) provide an attractive approach for implementing both broadband and application-specific matching networks within the photodiode package [12]. Direct integration of the MMIC minimizes RF parasitics and improves impedance matching at the chip-to-package interface. Compared with conventional surface-mount device (SMD) implementations, MMIC integration also reduces the number of discrete components and assembly steps, improving process reproducibility and facilitating automated manufacturing.

In this work, a backside-illuminated high-speed photodiode is integrated into a SWaP-optimized RF packages incorporating an MMIC-based matching network. Detailed RF simulation and optimization of the photodiode, ceramic carrier, MMIC, and package layout enable application-specific microwave responses while maintaining a 50 Ω interface. Prototype packaged photodiodes were manufactured using an automated assembly process and experimentally characterized to verify compliance with the target electrical and optical performance. The presented architecture

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demonstrates a practical approach toward industrial-scale manufacturing of high-performance RF photodiode modules for future radio-over-fiber satellite payloads.

2. PACKAGED RF PHOTODIODE

2.1 RF photodiode platform

The proposed packaged RF photodiode consists of a high-speed InGaAs/InP photodiode, an MMIC, a ceramic carrier, and a compact hermetic RF package. The platform enables both broadband and narrowband microwave operation through application-specific MMIC designs. By modifying only the MMIC, different microwave responses can be realized while preserving the photodiode chip, package platform, and manufacturing process.

In the broadband configuration, the photodiode reverse bias is supplied through an internal bias-T integrated within the MMIC (see Figure 1(a)), which implements a broadband resistive matching network. In the narrowband configuration (see Figure 1(b)), the photodiode is biased through the RF output using an external bias-T. The MMIC implements a reactive matching network that realizes application-specific narrowband microwave responses.

The packaged photodiode variants investigated in this work are summarized in Table 1.

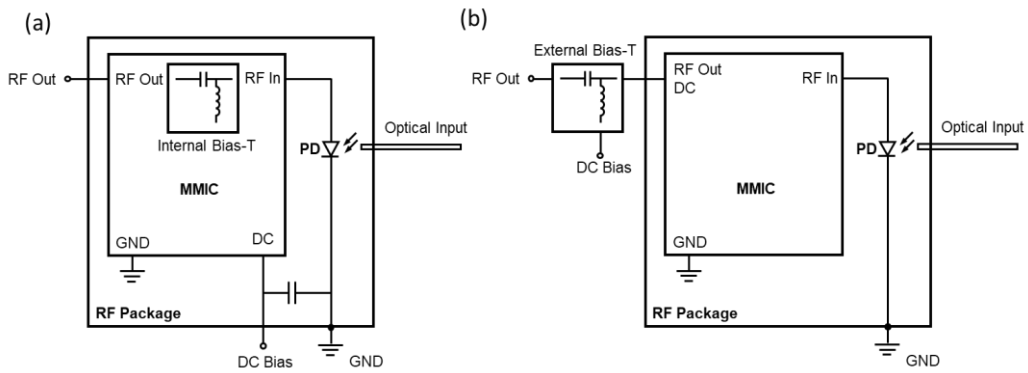


Figure 1. Schematic electrical layouts of the (a) broadband and (b) narrowband packaged photodiode configurations.

Table 1. Summary of the packaged photodiode variants and corresponding MMICs.

Product code	Description
PQS40M-L	Broadband packaged photodiode with MMIC matching (3 dB bandwidth > 30 GHz)
PQS03N-L	Narrowband packaged photodiode with MMIC matching within 2.85 – 3.5 GHz
PQS24N-L	Narrowband packaged photodiode with MMIC matching within 23.6 – 24.6 GHz

2.2 Photodiode

PD40X1 is a high-speed InGaAs/InP PIN photodiode employed in both the broadband and narrowband modules. As shown in Figure 2(a), the front side of the chip integrates the photodiode active area together with ground-signal-ground (GSG) contact pads. The backside of the InP substrate, shown in Figure 2(b), incorporates a monolithically integrated spherical lens with an anti-reflection coating, reducing the optical reflection below 1% at 1550 nm.

The backside integrated lens focuses the incident optical beam onto the active area on the front side of the device. This monolithic alignment provides high optical coupling efficiency and relaxed assembly tolerances.

At a wavelength of 1550 nm and a temperature of 25 °C, the photodiode exhibits a responsivity of 0.84 A/W (polarization-dependent loss < 0.05 dB). The small active area results in a junction capacitance of only 40 fF and a 3 dB electrical bandwidth of 38 GHz when measured on a 50 Ω load using an RF probe station.

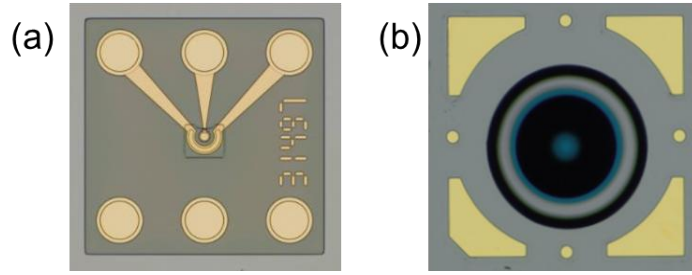


Figure 2. InGaAs/InP photodiode chip PD40X1 used in the module. (a) Front side with GSG contact pad layout. The vertically illuminated active area is located at the center of the chip. (b) Backside showing the monolithically integrated spherical lens with an anti-reflective coating, and its lens offset optimized for optical coupling.

2.3 MMIC

The MMIC integrated within the package serves as an impedance matching. It is fabricated using the PH10-10 GaAs process node from United Monolithic Semiconductors (UMS). This is a space evaluated technology listed in the European Space Agency's (ESA) European Preferred Parts List (EPPL) [13].

Minimizing the electrical distance between the photodiode and the matching circuit is critical for achieving adequate return loss over a wide frequency range. Simulations showed that conventional wire bonding interconnections would introduce excessive distance between the photodiode and the MMIC matching network. This is due not only to the actual length of the wire bonds but also to the clearances imposed by the wire bond tooling. To overcome this limitation, the MMIC designs employ the "hot via" option available in the UMS PH10 foundry process.

The hot-via technology enables the backside metallization of the MMIC to be patterned instead of forming a continuous ground plane, allowing RF signals to be routed through vias to the backside of the chip. Moreover, the backside of the MMIC is compatible with the same solder reflow process used for the photodiode chip. Alternatively, flip-chip mounting could provide a similarly compact solution but would require additional manufacturing steps, such as stud bumping and thermocompression.

Figure 3 illustrates the complete opto-electrical model implemented in Keysight ADS. The photodiode is represented by a voltage-controlled current source describing its responsivity, followed by a first-order low-pass filter accounting for charge carrier transit time. The cut-off frequency is estimated from opto-electrical measurements of a PD40X1 photodiode mounted on a test carrier. The parasitic elements of the photodiode are then represented by a series RLC model extracted from S-parameter measurements of the bare PD40X1 die. Finally, the impact of the packaging, including the transitions between the photodiode, ceramic carrier and MMIC, is incorporated using S-parameter data obtained from three-dimensional electromagnetic (3D EM) simulations in Ansys HFSS.

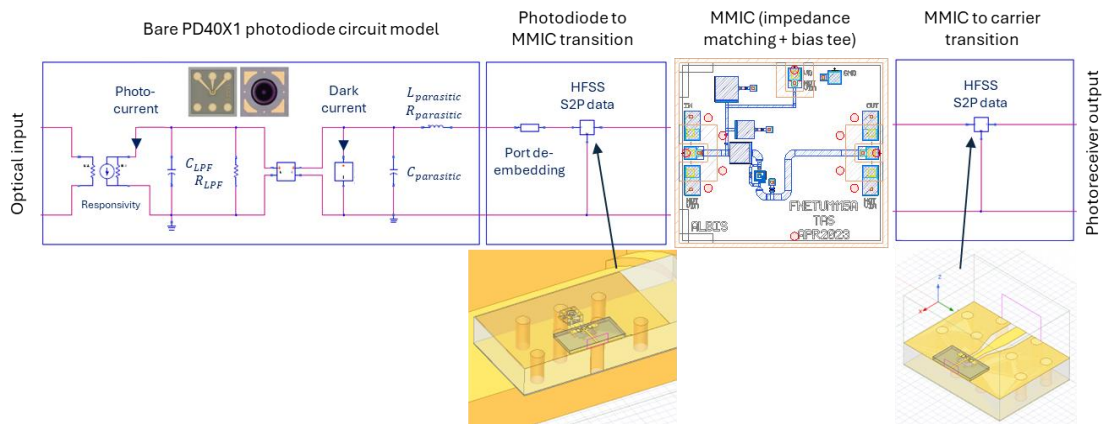


Figure 3. Keysight ADS 2-port opto-electrical model of the complete photoreceiver module featuring S-parameters from Ansys HFSS packaging simulations.

Figure 4 presents the simulated electrical return loss and transimpedance of the three designed MMIC variants together with the corresponding design targets (green lines). The broadband variant (PQS40M-L) provides broadband impedance matching beyond 30 GHz with a simulated transimpedance close to $25\ \Omega$. This is consistent with the performance expected from a purely resistive matching topology using a $50\ \Omega$ resistor in parallel with the photodiode. The other two variants (PQS03N-L and PQS24N-L) employ reactive matching networks centered around 3.2 GHz and 24.1 GHz, respectively, increasing the simulated transimpedance to 60 - 80 Ω within their passbands.

The results show that achieving both impedance matching and high conversion gain remains challenging for the broadband design. Despite being mounted as close to the photodiode as possible, the MMIC matching network is still located at a non-negligible electrical distance from the photodiode junction, making impedance matching difficult without sacrificing conversion gain. According to simulations, the narrowband designs exhibit improved impedance matching performance and significantly higher transimpedance within their operating bands compared with the broadband design.

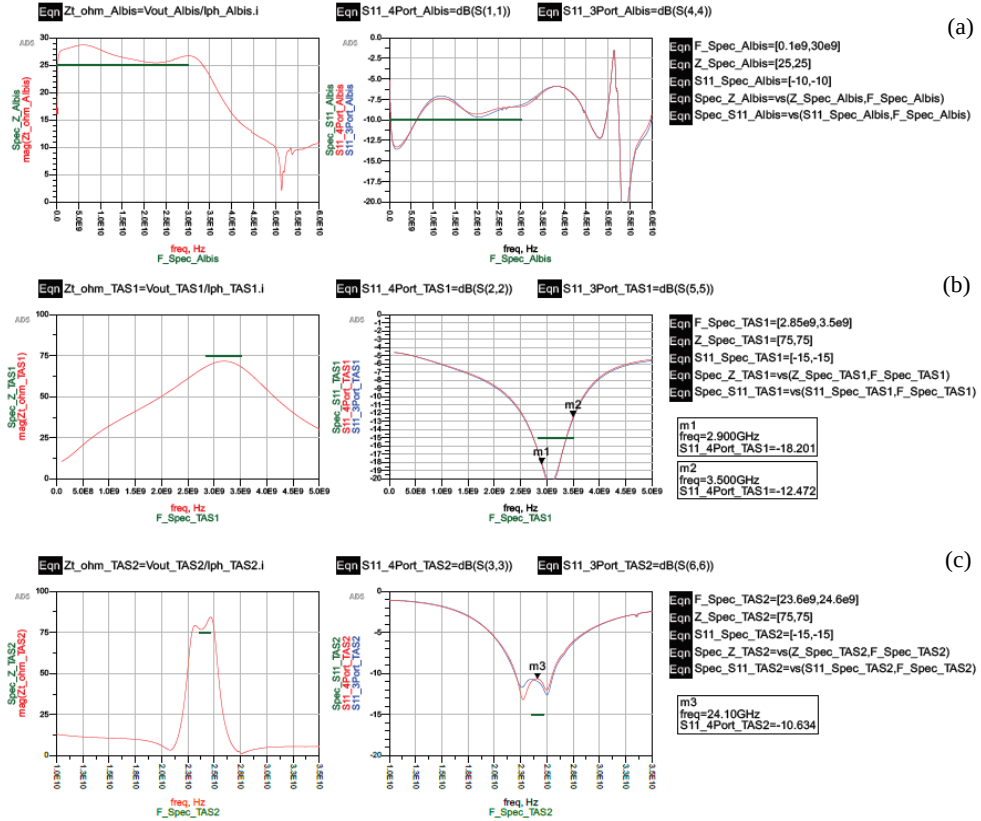


Figure 4. Simulated transimpedance (left) and electrical return loss (right) of the three packaged photodiode variants: (a) PQS40M-L, (b) PQS03N-L, and (c) PQS24N-L.

2.4 Fabrication

The packaged RF photodiode is assembled on an Al_2O_3 ceramic carrier, which serves as the common platform for the photodiode and MMIC chips. The PD40X1 photodiode and MMIC are positioned using an automated high-precision pick-and-place process with an accuracy better than $20\ \mu\text{m}$ before AuSn eutectic soldering. The resulting die attachment provides mechanical robustness, efficient thermal conduction, and consistent RF performance across assembled modules.

Following die attachment, the ceramic sub-assembly is integrated into an RF package optimized for low mass (below 10 g) and small dimensions ($9 \times 9 \times 13\text{ mm}$) suitable for space applications. Electrical interconnections between the sub-assemblies and the package feedthroughs are realized using SAC soldering with low solder temperature.

A single-mode 9/125 μm fiber pigtail is actively aligned to the photodiode chip and terminated with an FC/APC connector to minimize optical back reflections. After optical alignment, the package lid is hermetically sealed. Finally, hermeticity is verified using standard gross and fine helium leak tests.

Figure 5 shows the manufactured broadband RF photodiode module.

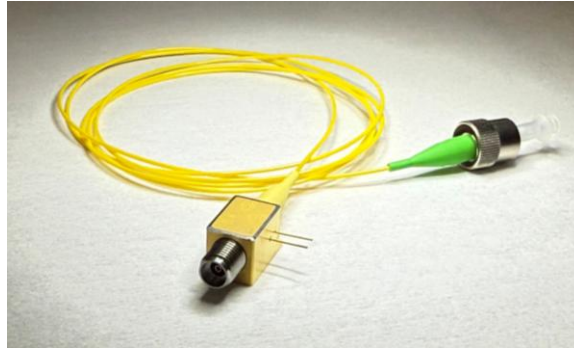


Figure 5. Manufactured broadband packaged photodiode module.

3. MEASUREMENT RESULTS

3.1 Measurement set up

The DC and RF opto-electrical (O/E) characteristics of the packaged photodiodes were measured using the experimental setup shown in Figure 6. The setup was used for DC characterization, S-parameter, and RF linearity measurements inside a temperature-controlled climate chamber.

A two-port vector network analyzer (VNA) was used to characterize the RF response of the device under test (DUT). Port 1 of the VNA drove an electro-optic (E/O) modulator, which generated a 1550 nm RF-modulated optical signal. The optical signal was subsequently amplified using an erbium-doped fiber amplifier (EDFA). The optical power was adjusted using a two-channel optical attenuator and coupled into the DUT through an optical circulator. The reflected optical power was monitored with an optical power meter for optical return loss (ORL) measurements. The RF output of the DUT was connected to Port 2 of the VNA, where the electrical return loss (S22) and O/E transmission response (S21) were measured.

The measured S21 includes the frequency responses of both the E/O modulator and the DUT. The frequency response of the E/O modulator was removed during post-processing so that the resulting S21 represents the O/E response of the packaged photodiode.

Broadband modules were biased through the dedicated DC pin, while narrowband modules were biased through the RF output using the VNA's built-in bias-T. During DC characterization, photocurrent was measured with a multimeter connected in series with the DUT.

Broadband frequency response was characterized at an optical input power of 0 dBm. The optical input power was subsequently increased to 11 dBm to evaluate RF saturation and determine the 1 dB compression point. Measurements were repeated at $-15\text{ }^{\circ}\text{C}$, $25\text{ }^{\circ}\text{C}$, and $100\text{ }^{\circ}\text{C}$ controlled by the climate chamber.

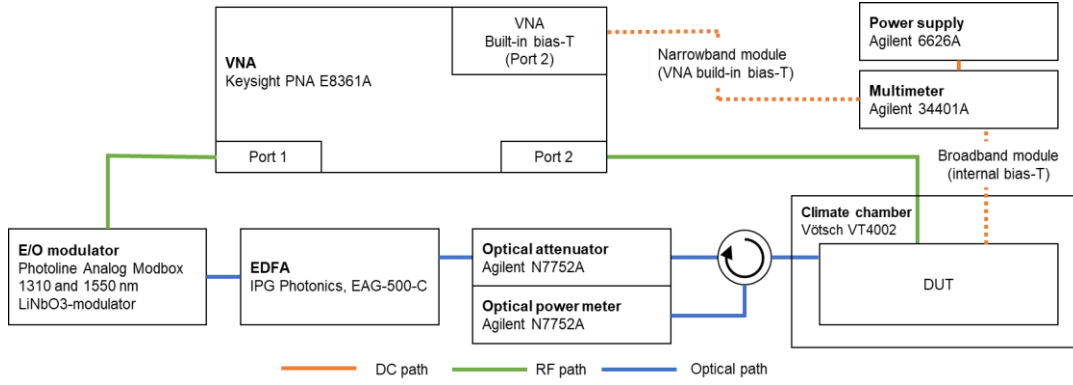


Figure 6. Schematic diagram of the experimental setup for the characterization of packaged photodiodes modules.

3.2 DC opto-electrical characteristics

The responsivity and optical return loss (ORL) of the broadband packaged photodiode PQS40M-L were characterized using a continuous-wave laser operating at a wavelength of 1550 nm. Measurements were performed at an applied reverse bias of 3.0 V over a temperature range from -15°C to 100°C . Figure 7 shows the measured responsivity and ORL of a representative broadband module.

The responsivity remains approximately 0.8 A/W over the investigated temperature range and decreases slightly at lower temperatures. Compared with the intrinsic responsivity of the PD40X1 photodiode, the measured value corresponds to an optical coupling efficiency of approximately 95% between the FC/APC connector and the photodiode chip.

The measured ORL remains close to 40 dB over the entire temperature range, indicating stable optical coupling and negligible temperature dependence of the optical interface.

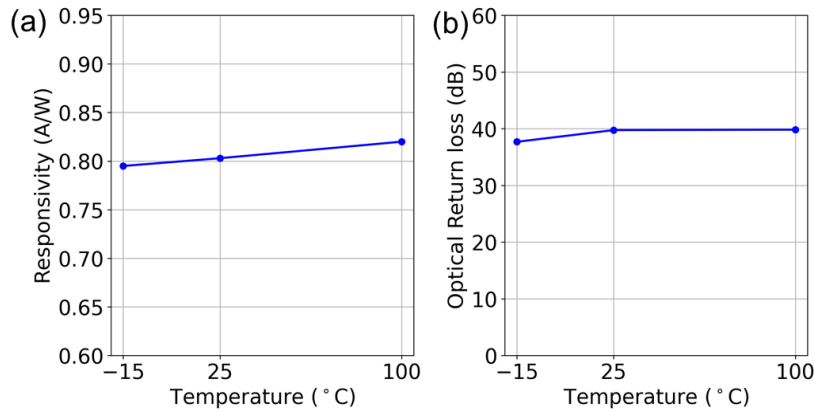


Figure 7. (a) Responsivity and (b) optical return loss of PQS40M-L measured at -15°C , 25°C and 100°C .

3.3 RF characterization

3.3.1 Broadband module

Figure 8 shows the O/E transmission response (S_{21}) and electrical return loss (S_{22}) of one representative broadband module PQS40M-L measured at -15°C , 25°C , and 100°C . Only minor changes are observed over the investigated temperature range, indicating good mechanical and electrical stability of the integrated photodiode module.

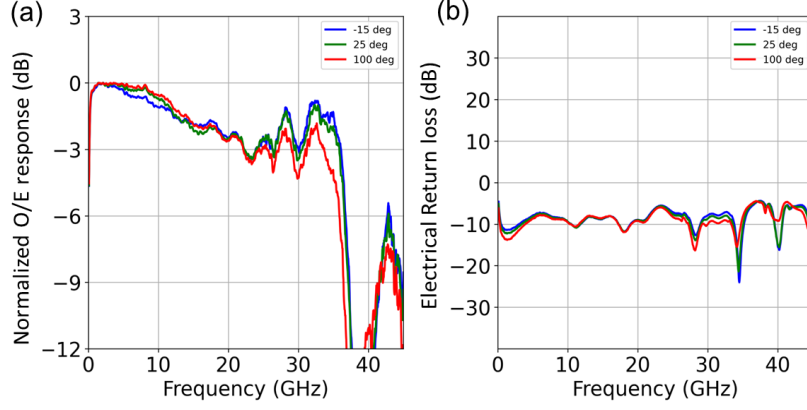


Figure 8. (a) O/E transmission response and (b) electrical return loss of PQS40M-L measured at -15°C , 25°C , and 100°C .

Figure 9 compares the measured O/E transmission response and electrical return loss of four PQS40M-L modules measured at 25°C . The modules exhibit an average 3 dB electrical bandwidth of 36 GHz, while the electrical return loss remains below -6 dB over this frequency range. The measured O/E response and electrical return loss are highly consistent among the four modules, confirming the reproducibility of the proposed packaging approach.

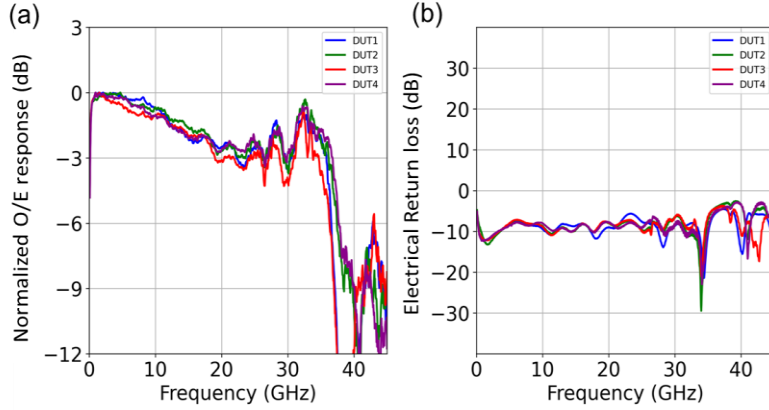


Figure 9. (a) O/E transmission response and (b) electrical return loss measured at 25°C for different PQS40M-L.

3.3.2 Narrowband module

Figure 10 and Figure 11 show the measured O/E transmission response (S_{21}) and electrical return loss (S_{22}) of the narrowband packaged photodiode variants PQS03N-L and PQS24N-L, respectively, measured at -15°C , 25°C , and 100°C . The measurements were performed at the nominal operating bias of 0.24 V.

For both modules, the electrical return loss remains below -10 dB within the specified operating band (2.85 to 3.5 GHz for PQS03N-L and 23.6 to 24.6 GHz for PQS24N-L) at 25°C , in good agreement with the simulated MMIC characteristics in Section 2.3. In addition, the measured 3 dB bandwidth fully covers the corresponding operating band. Only minor changes are observed over the investigated temperature range for both modules, consistent with the broadband module. These results confirm the versatility of the proposed photodiode platform for realizing application-specific microwave responses.

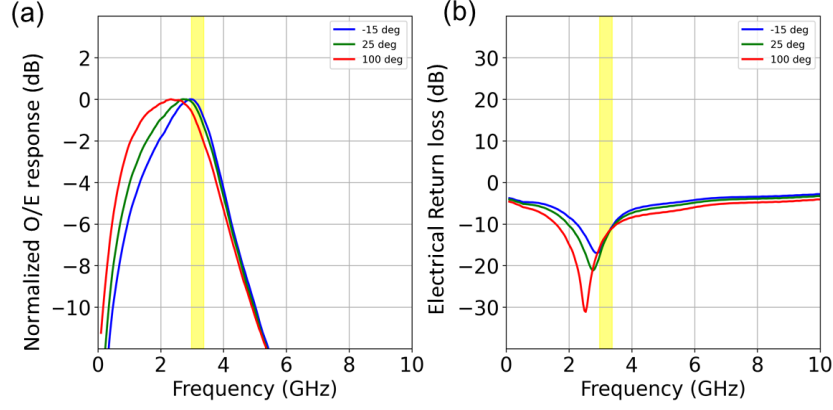


Figure 10. (a) O/E transmission response and (b) electrical return loss in the log-magnitude scale at different temperatures for PQS03N-L. The transparent yellow area highlights the specified operating band between 2.85 GHz and 3.5 GHz.

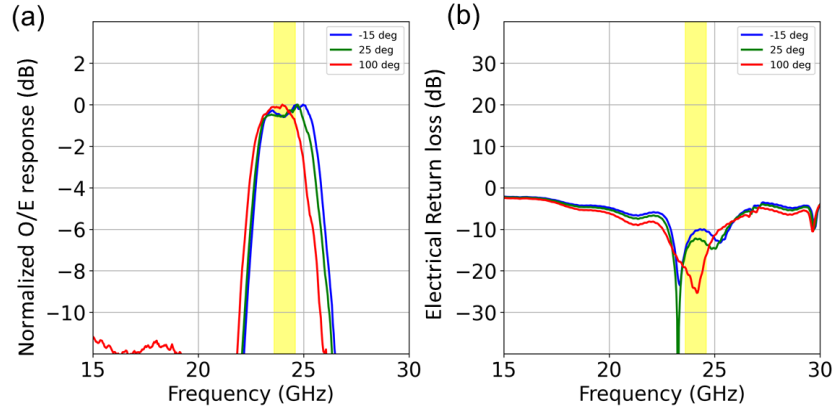


Figure 11. (a) O/E transmission response and (b) electrical return loss in the log-magnitude scale at different temperatures for PQS24N-L. The transparent yellow area highlights the specified operating band between 23.6 GHz and 24.6 GHz.

3.4 RF linearity

The RF linearity of the packaged photodiode was evaluated by measuring its 1 dB compression point. For photodiodes, RF linearity is commonly characterized by the average photocurrent at which the RF output power deviates by 1 dB from its linear response. The saturation current is defined as the photocurrent at the 1 dB compression point [14].

Figure 12 shows the RF linearity measurement of the PQS40M-L module at a fixed frequency of 28 GHz and a reverse-bias voltage of 3.0 V, measured at -15°C , 25°C , and 100°C . Figure 12(a) presents the measured RF output power as a function of photocurrent. Figure 12(b) shows the corresponding compression relative to the extrapolated linear response. Figure 12(c) summarizes the extracted saturation current at the three measurement temperatures. The saturation current decreases with increasing temperature.

The observed temperature dependence is attributed to the transport properties of the photogenerated charge carriers. As the optical input power and photocurrent increase, the power dissipated within the photodiode also increases, resulting in self-heating. At elevated temperatures, the carrier mobility, particularly the hole mobility, decreases, limiting carrier transport through the photodiode junction [15]. The resulting charge accumulation partially screens the electric field established by the applied bias voltage, leading to increased nonlinearity of the photodiode.

These results indicate that the proposed package architecture supports high-linearity operation over the investigated temperature range.

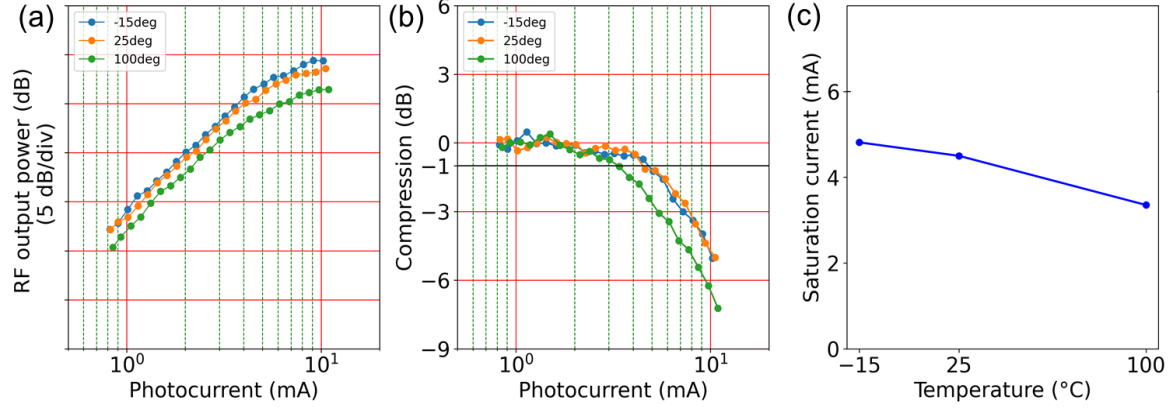


Figure 12. (a) RF output power and (b) RF compression as a function of photocurrent for PQS40M-L at 28 GHz and different temperatures. The solid line in (b) indicates the -1 dB level. (c) Extracted saturation current at different temperatures.

4. CONCLUSION

We demonstrated a proof-of-concept SWaP-optimized packaged RF photodiode platform with application-specific microwave responses enabled by MMIC-based matching networks. The proposed architecture allows broadband and narrowband frequency variants to be realized while preserving a common photodiode platform and assembly process. The measured results confirmed reproducible RF performance, stable operation over a wide temperature range, and high RF linearity, demonstrating the versatility of the proposed approach.

The simulation-driven MMIC design and semi-automated assembly process provide a scalable manufacturing route with improved reproducibility and reduced RF variation compared with conventional wire-bond-based implementations. By eliminating discrete matching components and minimizing assembly complexity, the proposed platform is well suited for scalable and cost-effective production of high-performance packaged photodiodes.

The presented platform establishes a foundation for future developments, including the integration of active RF amplification within the package. Beyond the demonstrated broadband and narrowband modules, the same design methodology can be extended to other application-specific frequency bands for satellite payloads, as well as terrestrial radio-over-fiber and phased-array antenna systems.

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