Advancing Detector Shielding with Thermo-Optic Defocusing in PMMA Integrated on Silicon Nitride

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Abstract: This study develops an on-chip optical power limiter (OPL) based on the thermo-optic defocusing effect in PolyMethyl-Methacrylate (PMMA) to protect an avalanche photodiode (APD) from high optical power damage. The OPL is designed to operate within a reduced power range of 0.1 mW to 10 mW by adjusting waveguide dimensions, taper widths, and free-space region (FSR) lengths. Detailed calculations, modelling, and simulations are presented, demonstrating the efficacy of the OPL in limiting optical power reaching the APD, preventing damage and ensuring stable performance in high-power applications.

1 INTRODUCTION

Silicon photonics plays a pivotal role in data communications, quantum key distribution (QKD), and sensing applications. As these systems evolve, protecting photonic circuits from high-intensity optical signals becomes crucial, particularly for safeguarding sensitive components like avalanche photodiodes (APDs). Optical Power Limiters (OPLs) (Lee, 1993) are essential for preventing damage from excessive power and ensuring stable operation. While technologies such as silicon waveguides with strong two-photon absorption (Osgood, 2009) and photonic crystals (Zheng, 2015) face limitations in integration and fabrication, polymer-based OPLs, like those using PMMA (Gandhi, 2024), offer advantages in thermal management and power handling. This paper presents a PMMA-based OPL design using the thermo-optic defocusing effect to protect APDs, ensuring reliable performance and extending device lifespan in variable environments. Avalanche photodiodes (APDs) are widely used in high-speed optical communication systems due to their high sensitivity. However, they are prone to damage when exposed to optical powers beyond a few milliwatts. Therefore, an optical power limiter (OPL) is essential to protect APDs from high intensity light. In this paper, we design an OPL that operates in the power range of 0.1 mW to 10 mW. The OPL employs a thermo-optic defocusing mechanism in PMMA, a material with a negative thermo-optic coefficient. This mechanism induces beam divergence with increasing input power, which limits the amount of light reaching the APD. Building on the principles from our high-power OPL designs, we reduce the maximum limiting power range from 10 mW - 102 mW to 0.1 mW - 10 mW.

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2 OPL DESIGN

The OPL design incorporates a pair of tapered waveguide antennas separated by a free-space region (FSR) filled with PMMA, modelled as a dielectric material with refractive indices of 1.4716 and 4.04 × 10-6 and a thermal optic coefficient of -1.3 × 10-4 K-1 as shown in figure 1. Using COMSOL Multiphysics for 3D thermal-optic simulations for the free-space region (FSR) and nonlinear regression model for output threshold power. Our devices exhibited insertion losses between 2.5 and 10 dB and maximum powers in the range of 10 to 102 mW, demonstrating effective on-chip optical power limiters based on thermal defocusing effects (Gandhi, 2024).

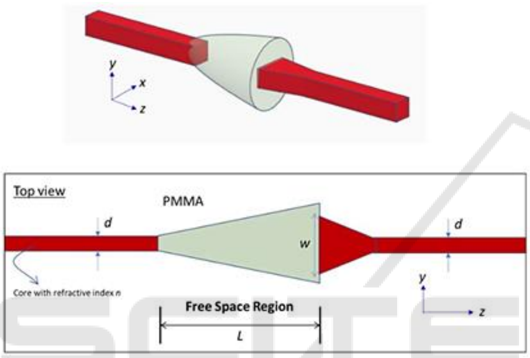

Figure 1: Schematic of the on-chip optical power limiter.

2.1 Theory

The core mechanism behind this OPL is the thermo-optic effect in PMMA, where the refractive index decreases with increasing temperature due to the negative thermal-optic coefficient. The change in the refractive index Δn of PMMA is given by $\Delta n{=}n$ $+\beta\Delta T$, where n = 1.4716 (refractive index at room temperature), β=−1.3×10 K (thermal-optic coefficient), ΔT is the temperature rise. For powers between 0.1 mW and 10 mW, we estimate the temperature rise as $\Delta T{=}\ \alpha P,\ with$ α=0.5 K/mW.

Hence ΔT (0.1 mW) =0.05 K, Δn= −6.5×10, ΔT (1 mW) =0.5 K, Δn=−6.5×10, ΔT (10 mW) =5 K, Δn=−6.5×10. For low powers, the output power Pout closely follows the input power. However, as power increases, the output power saturates due to the decreased CE. Figure 2 depicts the relationship between input power and output power.

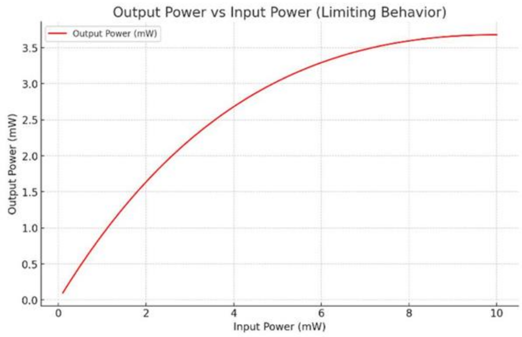

Figure 2: Output Power vs. Input Power.

This leads to increased beam divergence as the input power increases. The divergence angle $\theta(P)$ of the beam in the free-space region (FSR) is a function of input power P.

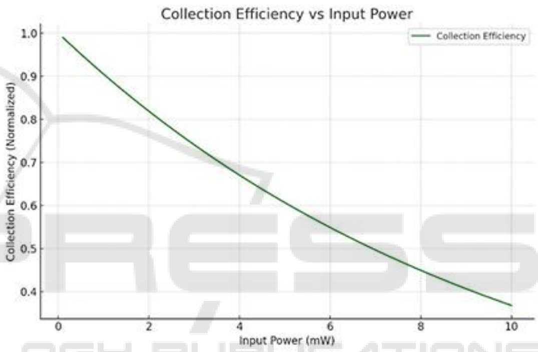

Figure 3: Collection Efficiency vs. Input Power.

At low powers, the divergence angle follows a Gaussian beam, while at higher powers, it becomes a nonlinear function: $\theta(P)\ =\ \theta\ \circ\ +kP$ where θ is the divergence angle of the equivalent Gaussian beam in the low-power regime, k is a constant depending on the material and waveguide geometry, P is the input optical power. Therefore, for input power = 0.1 mW, 1 mW, and 10 mW, the divergence angles are 2.04, 2.4º and 6º respectively. As beam divergence increases with power, the collection efficiency (CE) at the output waveguide decreases as shown in figure 3. $CE(P)\ =\ CE\ \cdot\ e$ where CE is the initial collection efficiency at low powers, k is the same constant as in the divergence equation. The CE for powers of 0.1 mW, 1 mW, and 10 mW are 0.89, 0.82 and 0.37 respectively, give CE =0.9 and k=0.1. In the linear regime (low power), insertion loss (IL) is given by the ratio of output power $Pout$ to input power Pin. $IL\ =\ 10log(Pin/Pout)$. In the nonlinear regime, insertion loss increases rapidly with input power. The OPL demonstrates insertion losses ranging from 2.5 to 6.0 dB across the tested input power levels. The low insertion loss is crucial for keeping signal integrity in optical systems.

2.2 Geometrical Adjustments and Defocusing Effect

To obtain the optimal structure for the Optical Power Limiter (OPL) design, we performed a detailed numerical analysis of how varying input power affects output power under different geometrical configurations. By adjusting the waveguide width, taper length, and Free-Space Region (FSR) length, we observed their combined effects on the defocusing behaviour caused by the thermo-optic effect in Poly-Methyl-Methacrylate (PMMA). The analysis showed that the optimal structure for maximum power limiting involves a small waveguide width of 3 µm, a short taper length of 200 µm, and a compact FSR length of 1 mm.

3 CONCLUSIONS

This configuration maximises beam divergence at lower input powers by confining the optical mode more tightly, which accelerates the thermo-optic defocusing effect. A smaller waveguide width increases mode confinement, enhancing the defocusing and saturating output power faster at high input levels. The short taper length ensures a quicker transition to a diverging beam profile, while the short FSR confines the beam’s interaction distance, promoting more significant refractive index changes in the material. Together, these parameters ensure that the output power remains low (below 1 mW) across a wide input range (up to 50 mW), providing effective protection for sensitive devices like avalanche photodiodes (APDs). This design offers technical significance by preventing potential damage to APDs in high-power applications, ensuring safe operation while improving the OPL's efficiency.

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