WHITE PAPER :

ENHANCING LASER GUIDANCE PERFORMANCE WITH ELFYS BLACK SILICON 4-QUADRANT PHOTODIODES

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ABSTRACT

This white paper presents ElFys patented black silicon photodiode technology for semi-active laser (SAL) guidance systems operating at the 1064 nm wavelength used in Nd:YAG laser-guided munitions. By utilizing nanostructured black silicon surfaces to minimize reflection losses and enhance near-infrared absorption, ElFys photodiodes achieve significantly higher responsivity than conventional silicon quadrant detectors while maintaining the fast response times required for NATO-compliant laser pulse detection.

The Black Silicon QPD product line delivers >30 % higher responsivity (0.64 A/W) at 1064 nm with a 12 ns rise time, which results in a 50 % increase in target acquisition range and reliable operation in obscured environments, as demonstrated by an OEM manufacturer of laser-guided artillery systems. Environmental qualification testing further demonstrates the robustness of the technology under extreme thermal, mechanical, humidity, and radiation conditions, making it well suited for demanding defense applications.

Key Points:

- Advancing Semi-Active Laser Guidance at 1064 nm
- Enhanced Detection in Challenging Environments
- Proven Range and Tracking Performance Improvements
- Black Silicon Technology for Next-Generation NIR Sensing

About the Author:

Toni Pasanen works at ElFys, Inc. as a Senior Project Engineer and is one of the co-founders of the company. He holds a D.Sc. (Tech.) degree in Micro- and Nanosciences from Aalto University, Finland, and has a background in applied research on semiconductor-based optoelectronic devices.

He has several years of experience in the design and fabrication of various types of advanced light and radiation detectors and solar cells, as well as strong expertise on nanostructured black silicon surfaces and thin films. Dr. Pasanen has authored tens ,of peer-reviewed scientific articles, written a book chapter about the properties and applications of black silicon, and presented his research in several international conferences.

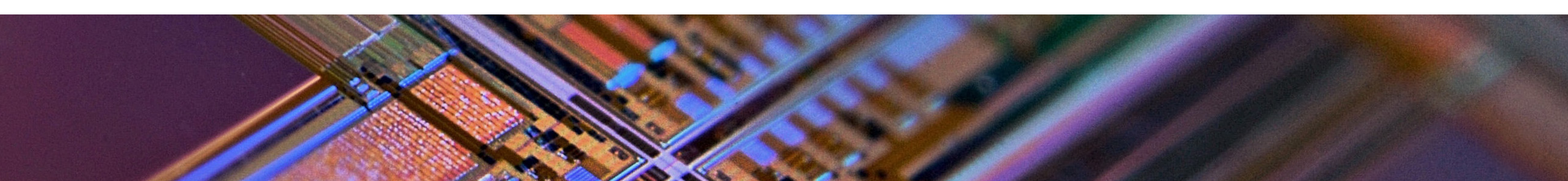
INTRODUCTION

The detection of near-infrared (NIR) radiation is critical to a wide range of modern defense and security systems. In particular, radiation at a wavelength of 1064 nm emitted by neodymium-doped yttrium aluminum garnet (Nd:YAG) lasers is of significant interest. One of the most prominent applications operating at this wavelength is laser-guided munition, such as missiles, bombs, or artillery shells. In such systems, precise detection of laser radiation is required to determine the position of a designated target and to guide the munition accordingly. This function is typically enabled by position-sensitive photodetectors, such as four-quadrant photodiodes, which provide continuous spatial information about the incoming laser signal. The performance of these detectors directly impacts the accuracy, responsiveness, and reliability of the overall guidance system. Silicon photodetectors are commonly used in these applications due to their availability, mature fabrication processes, and cost-effectiveness. While silicon performs exceptionally well for visible light detection, conventional silicon-based photodiodes face inherent limitations in the NIR spectral range. In particular, the absorption of silicon decreases at longer wavelengths, leading to reduced responsivity at 1064 nm. Given these limitations, there is a clear opportunity for innovative solutions that can overcome the inherent constraints of silicon-based photodetectors used in laser-guided munition. ElFys patented black silicon technology provides a powerful solution by leveraging nanostructured surfaces to dramatically enhance NIR absorption, enabling high-performance silicon photodiodes at the critical wavelengths.

SEMI-ACTIVE LASER GUIDANCE EXPLAINED

Laser guidance systems, also called semi-active laser (SAL), are widely used in precision munitions to strike targets with high accuracy. In such systems, a laser designator is used to mark, or “paint” the target with a beam at 1064 nm (Figure 1). The operator illuminates the target using a YAG laser designator, which may be handheld by ground-based infantry or mounted on a platform such as an aircraft. The laser beam reflects off the target surface, creating a spot which the seeker head of the missile or artillery shell can detect and track.

After launch, the munition follows an initial trajectory and is often guided by inertial navigation toward the general target area. As the munition approaches the vicinity of the target, an onboard laser seeker is activated. This seeker detects the reflected laser radiation using a location-sensitive NIR photodetector and determines the location of the laser spot. The detected signal is continuously processed by the guidance control system, which translates it into real-time trajectory corrections. These adjustments are implemented through the munition’s guidance fins or thrust vectoring systems to keep the missile or artillery shell aligned with the reflected laser signal and accurately home in on the target.



Laser beam tracking systems used in seeker heads rely on rapid and precise photodetection to monitor the position of the incoming signal. These systems commonly employ a 4-quadrant photodetector, which is a sensor where the detection area is divided into four equal segments. As a laser beam shines onto the detector surface, the position of the beam on the surface determines the amount of light received by each of the four quadrants. Each quadrant generates a photocurrent proportional to the received light intensity. By comparing the relative signal levels between the quadrants (e.g., top vs. bottom, left vs. right), the system can accurately determine the beam position relative to the detector center (Figure 2). This positional information is fed to the control system, which continuously adjusts the tracking and guidance to maintain alignment.

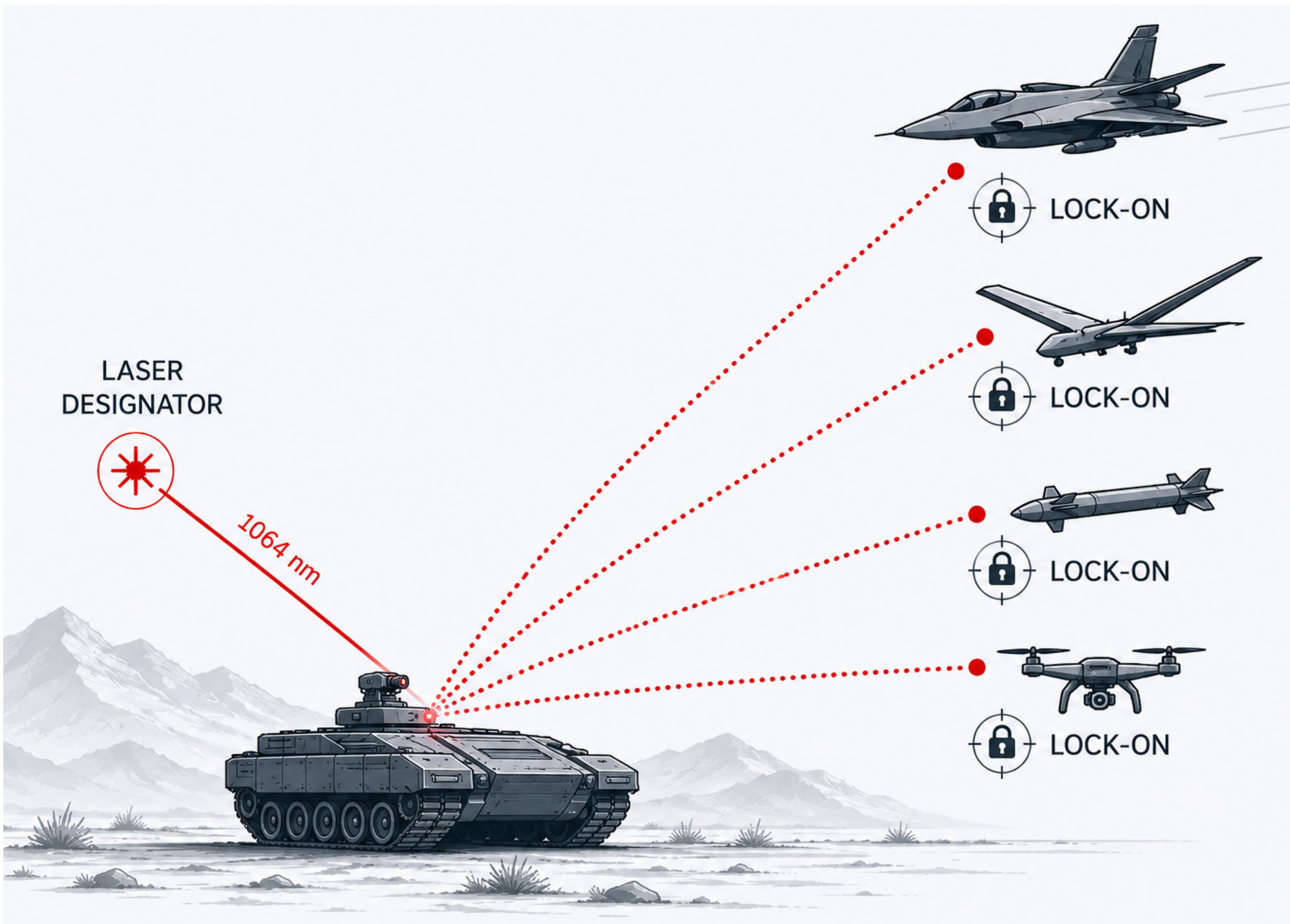
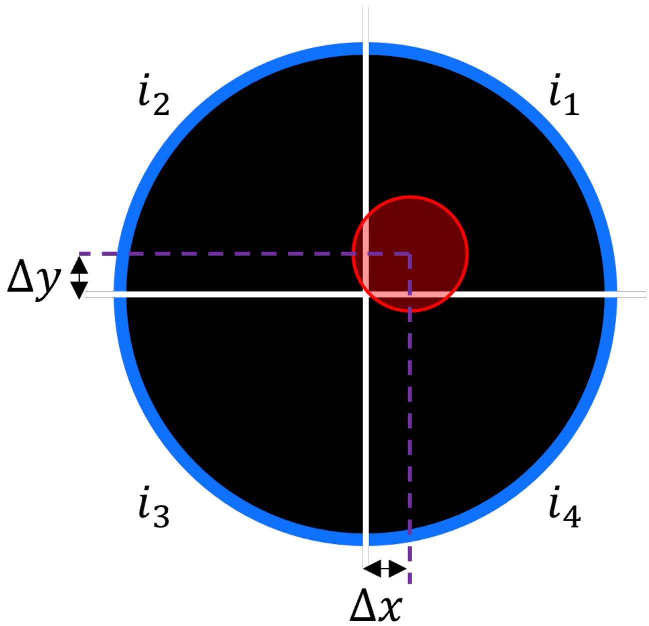


Figure 1. The operating principle of YAG-laser munition guidance.

Such systems impose stringent performance requirements on the photodetector. The high velocity of the munition demands the photodetector to respond promptly to changes in light intensity to avoid missing the target. To ensure reliable target identification and minimize interference from other sources, the designator operates in a coded pulse mode, emitting a specific temporal pulse sequence. The pulse width ranges from 10 to 25 ns according to the commonly used NATO standards, imposing stringent speed requirements on the photodetector. At the same time, high responsivity is critical, as the received optical signal may often be weak due to the long distance to the target and environmental attenuation caused by smoke, rain, fog, or other obscurants.



$$x = \frac{(i_1 + i_4) - (i_2 + i_3)}{i_1 + i_2 + i_3 + i_4}$$

$$y = \frac{(i_1 + i_2) - (i_3 + i_4)}{i_1 + i_2 + i_3 + i_4}$$

Figure 2. A 4-quadrant detector can determine the position of a laser beam on the detector surface by comparing the output currents between the quadrants.

ENHANCED RESPONSIVITY VIA BLACK SILICON

When light reaches the surface of a photodetector, a portion is reflected due to the refractive index mismatch between air and the detector material. This reflection loss can significantly reduce the amount of light entering the device that is available to be converted into electrical signal. For a bare silicon surface, reflectivity can be as high as ~30 % at normal incidence in the NIR range, meaning that nearly one-third of the incident light is lost before it reaches the active region, resulting in a corresponding reduction in responsivity.
A widely used method to mitigate these optical losses is the application of an anti-reflection (AR) coating. Such coatings consist of thin dielectric layers with refractive indices intermediate between air and silicon. By inducing destructive interference of reflected light waves, AR coatings reduce reflection from the surface and enhance photon absorption in silicon. The material composition and thickness of the coating are carefully optimized to minimize reflection within a targeted wavelength range.

ElFys has developed an alternative, advanced approach for reflectance reduction: nanostructured black silicon, which exhibits unique optical properties. Black silicon consists of nanostructures smaller than the wavelength of light that form an effective medium with a gradual refractive index transition from air to silicon. The nanostructures virtually eliminate the optical interface between these two materials and efficiently suppress reflections across a broad range of wavelengths and incident angles from ultraviolet to visible and NIR.

In addition to its anti-reflective properties, black silicon provides further optical advantages. Its irregular surface morphology promotes scattering of incident light, effectively increasing the optical path length within the silicon material. This enhances the probability of photon absorption, particularly at NIR wavelengths beyond 1000 nm where silicon absorption is inherently weak and which are used in laser-guided munition. As a result, black silicon enables thinner photodetector structures with equal or superior absorption compared to thicker conventional devices. This, in turn, allows for a more optimal combination of high responsivity and fast speed, providing greater flexibility in optimizing device performance for a specific application and boosting the photodetection performance in laser-guidance systems.

BLACK SILICON 4-QUADRANT DETECTORS

One of the main challenges associated with conventional 4-quadrant detectors is their limited responsivity at 1064 nm, while still meeting the high-speed performance requirements of laser guidance systems. Conventional silicon photodiodes typically exhibit responsivity below 0.5 A/W at this wavelength at room temperature, even with an optimized AR coating. ElFys addresses this limitation by introducing the Black Silicon QPD product line, designed to deliver both high responsivity and fast response at 1064 nm. This product family consists of 4-quadrant photodiodes featuring a black Si photosensitive surface arranged in a circular geometry with four individual pixels (Figure 3). The standard products have a diameter of 14 mm with an active area of 38.5 mm2 per quadrant element. All photodiodes are housed in a hermetically sealed TO-can package. Two standard variants are available: The QPD-385-YH includes an integrated heater and temperature sensor, while the QPD-385-Y comes without capabilities for thermal control. The photodiode and its package have been optimized for 1064 nm wavelength – the glass window induces no optical losses around this region thanks to the optimized antireflection (AR) coating.

Figure 3. Black Silicon 4-quadrant detector die and packaged component optimized for 1064 nm wavelength.

Table 1 presents the key electrical parameters of the ElFys QPD-385-Y(H) product, compared to other state-of-the-art quadrant diodes with similar size. All diodes have been optimized for the 1064 nm wavelength, and the shown data represents typical values of the packaged components. By enhancing light absorption and minimizing losses due to reflection, the black silicon photodiodes exhibit higher quantum efficiency, translating to improved responsivity. Indeed, ElFys black silicon 4-quadrant detectors achieve responsivity of 0.64 A/W for 1064 nm at room temperature, representing more than 30 % improvement compared to conventional technologies. The rise time of the black photodiodes is 12 ns, ensuring compatibility with the NATO STANAG 3733 that defines the characteristics of pulsed lasers used for target designation and weapon guidance. Other optoelectronic parameters are essentially very similar to other 4-quadrant detectors, with somewhat lower dark current in the ElFys photodiode.

Table 1. Comparison of ElFys QPD-385-Y(H) black Si 4-quadrant photodiode with 14 mm diameter to other state-of-the-art quadrant diodes with similar size. All data presents the typical performance at room temperature, as reported in the publicly available datasheets. The main difference is the >30 % higher responsivity at 1064 nm.

Model	Responsivity 1064 nm (A/W)	Rise Time 50 Ω (ns)	Dark Current per Element (nA)	Capacitance per Element (pF)
ElFys QPD385-Y(H)	**0.64**	12	5	15
4-quadrant diode A	0.47	12	50	12
4-quadrant diode B	0.40	18	50	15
4-quadrant diode C	0.48	12	10	14

CUSTOMER CASE EXAMPLE: LASER-GUIDED ARTILLERY

The greatly enhanced performance of ElFys black 4-quadrant photodiodes delivers substantial benefits in laser guidance systems. An OEM manufacturer of laser-guided artillery evaluated ElFys 4-quadrant photodiodes for integration into the semi-active laser seeker of a laser-guided artillery round. According to the independent evaluation results, the system with ElFys black 4-quadrant detector successfully achieved 5 km acquisition range, which is a 50 % increase in comparison to existing photodetector used on the market under the same testing conditions. The operation also verified excellent performance under environmental obscurants, including moderate rain and light cloud cover, which is typically a difficult task for laser-guided artillery.

The extended acquisition range provides significantly more time for trajectory correction, improving weapon accuracy and reducing circular error probable (CEP). In addition to the performance gains, the longer acquisition distance enables cost savings for the OEM. These savings arise from reduced control surface area of the artillery shell, the ability to use a lower-cost inertial measurement unit (IMU), and a smaller 25 mm optical aperture which is critical for mechanical integration within the highly constrained volume of an artillery round.

The higher responsivity of the black silicon 4-quadrant photodiodes also gives more freedom in selecting the temperature operating point. To reach the responsivity of 0.64 A/W that the black Si diodes provide at room temperature, conventional quadrant detectors need to be heated up to about 50-60 °C, indicating that less or even no heating is needed to reach the required signal level with the black Si detector. On the other hand, when the 4-quadrant diodes are kept in a cold environment before use, which is the case, e.g., when the photodiode is used in a guided munition that will be launched from an airplane, the black Si photodiodes need to be heated up to only around -20 °C to reach the responsivity of 0.4-0.48 A/W which the other quadrant detectors reach at room temperature. This means that the ElFys black Si photodiodes give the needed level of signal faster compared to other available 4-quadrant detectors.

Figure 4. According to the independent evaluation results, the system with ElFys black 4-quadrant detector successfully achieved 5 km acquisition range, which is a 50 % increase in comparison to existing photodetector used on the market under the same testing conditions

ENVIRONMENTAL STABILITY

When used as a part of a seeker head in munition guidance systems, photodiodes are often subjected to harsh environmental conditions and rapid changes in them. To ensure that ElFys black Si photodiodes meet the stringent requirements of such systems, their stability has been tested under a range of environmental stresses and treatment conditions.

Table 2 summarizes the conducted stability tests, the applied standards or test conditions, and the measurement results. Most of the test were carried out at the accredited test laboratory of Etteplan Finland Oy. The detectors have been subjected to cycling between low (-55 °C) and high (125 °C) temperatures, as well as thermal shock by rapid transfer from freezing conditions to environments exceeding 65 °C. Mechanical durability has been assessed through vibration testing simulating helicopter transport and high-G shock testing representative of missile launch conditions. In addition, the devices have been exposed to prolonged high-temperature and high-humidity environments, as well as proton and electron irradiation. ElFys photodiodes have successfully passed all conducted tests, demonstrating the suitability of the products for laser guided munition systems.

Table 2. Summary of the environmental stability tests that have been performed on ElFys products.

Test	Standard / Conditions	Result
Temperature cycling	MIL-STD-883, Test Method 1010, Test Condition B	Pass
Vibration	MIL-STD-883, Test Method 2007, Test Condition A	Pass
Humidity	70 °C, 70% Relative Humidity, 500 h	Pass
Temperature shock	MIL-STD-810G/1, Test Method 503.6, Procedure I-C	Pass
High G shock	MIL-STD-810G/1, Test Method 516.7, Procedure I	Pass
Proton irradiation	ESCC Basic Specification No. 22900	Pass
Electron irradiation	ESCC Basic Specification No. 22900	Pass

CONCLUSION

The results presented in this paper demonstrate that black silicon technology overcomes the key limitations of conventional silicon photodiodes at 1064 nm and enables a new level of performance for semi-active laser guidance systems. By significantly increasing responsivity while maintaining nanosecond-level response times, ElFys black silicon 4-quadrant detectors improve target acquisition capability, tracking reliability, and guidance accuracy under challenging operational conditions.

The combination of enhanced detection performance, reduced heating requirements, and proven environmental robustness provides clear system-level advantages for laser-guided munitions and other defense applications operating at 1064 nm. These benefits can translate into longer acquisition range, improved resistance to environmental obscurants, reduced seeker complexity, and lower overall system cost. As a result, ElFys black silicon photodiodes represent a highly effective and scalable solution for next-generation NIR detection systems where both high sensitivity and high speed are required.

ABOUT ELFYS,INC.

ElFys, Inc. was founded in 2017 and is located in Espoo, Finland. The company is based on long-term research work on photodetector technologies at Aalto University. Our core team consists of former senior researchers, engineering leaders and business professionals. The company utilizes the state-of-the-art processing facilities at Micronova Nanofabrication Center in Espoo, Finland: 2600 square meters of CMOS compatible facilities suitable for both R&D and semi-mass production. For high-volume mass production, ElFys has partnered with an external, European foundry.

ElFys provides light sensors with better sensitivity than anything seen before, literally catching every ray of light. The technology greatly improves any light sensing application ranging from health monitoring to analytical instrumentation and security X-ray imaging. The superior performance of ElFys photodetectors is based on an inventive combination of modern MEMS nanotechnology and atomic layer deposition. The core technologies are patented and in the possession of the company.

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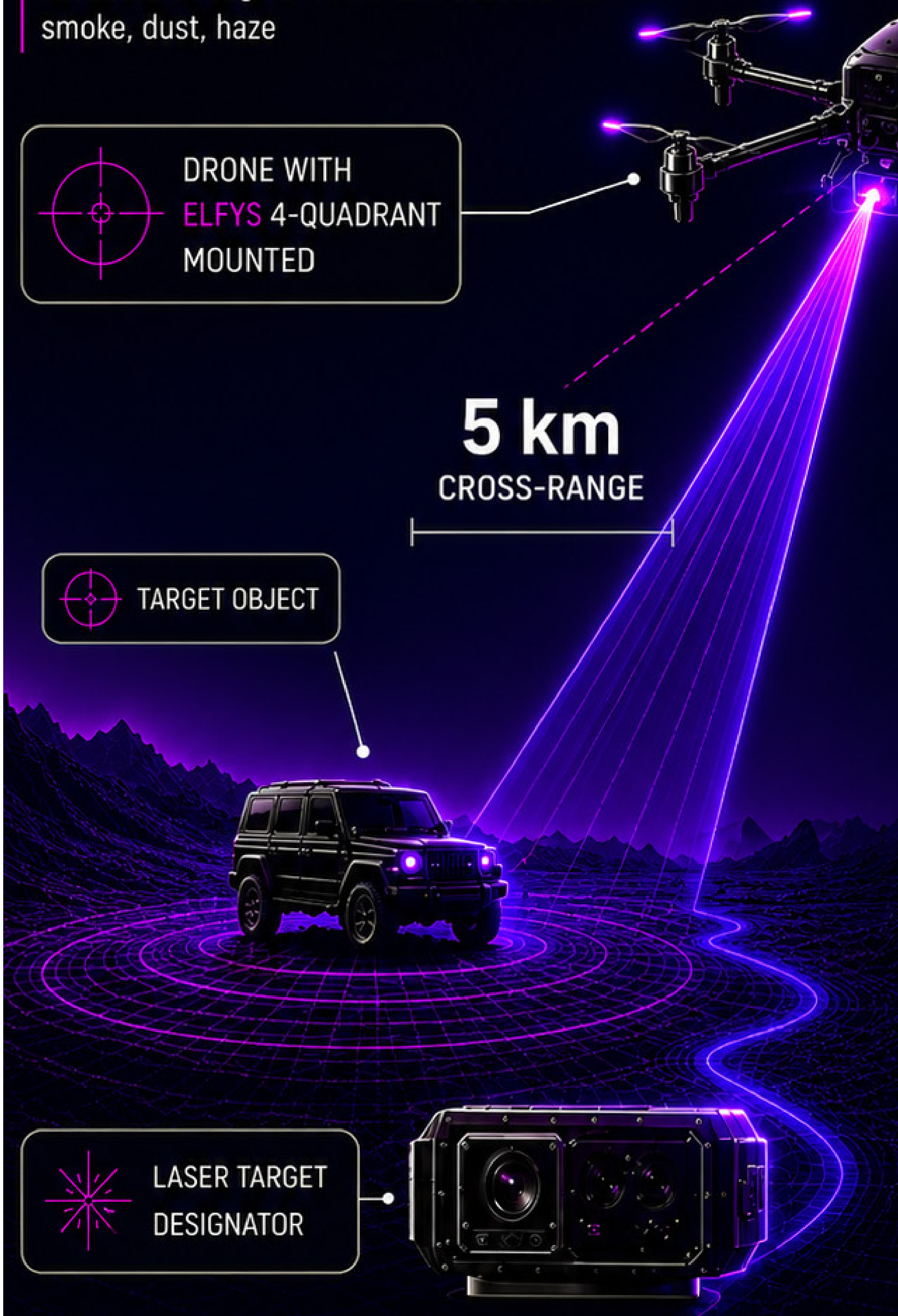

ELFYS 4-QUADRANT SILICON DETECTOR

- HIGH SENSITIVITY
- LOW NOISE
- FAST RESPONSE
- BROAD DYNAMIC RANGE

ELFYS 4-QUADRANT SILICON DETECTOR

- HIGH SENSITIVITY
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