Beam Quality, Power, and Reliability: The Case for PCSELs in FSOC Systems

White Paper

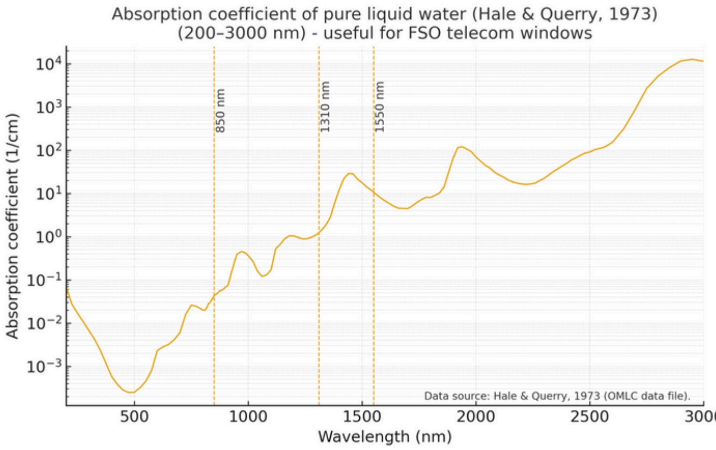
INTRO

Free space optical communication (FSOC) is like fibre-optic internet without the cables. Data streams carried not through glass cables but across open air and even outer space. Using lasers, FSOC can deliver blisteringly fast speeds rivalling fibre, with beams so narrow they're nearly impossible to intercept, making them naturally secure compared to other RF based systems. Because it doesn't rely on spectrum licenses or digging trenches for cables, FSOC can be deployed rapidly, bridging the "last mile" between buildings, powering 5G backhaul, or linking satellites in orbit. Its Achilles' heel lies in the atmosphere: fog, rain, and turbulence scatter light and can snap the fragile line-of-sight connection. As engineers push past Earth's weather with adaptive optics and shift to the vacuum of space, FSOC is already revolutionising satellite networks and interplanetary communication. It's the promise of fibre-optic capacity, but free of the ground.

REQUIREMENTS FOR FSOC DEVICE

The laser sources required for FSOC must meet stringent technical specifications to ensure reliable, high-capacity links. Operating wavelengths are typically centred at 850 nm or 1550 nm, corresponding to atmospheric transmission windows and the availability of high-performance detectors. The 1550nm band is generally preferred, as it permits higher launch powers within IEC/ANSI Class 1M eye-safety limits while minimising atmospheric absorption.

Lasers must exhibit narrow spectral linewidths (on the order of MHz or less) to support advanced modulation formats and coherent detection, with low relative intensity noise (RIN) and excellent beam quality ($M^2 \approx 1$) to minimise divergence losses. Output powers often range from tens to hundreds of milliwatts for terrestrial links, scaling higher for space-based terminals where link budgets are more demanding.

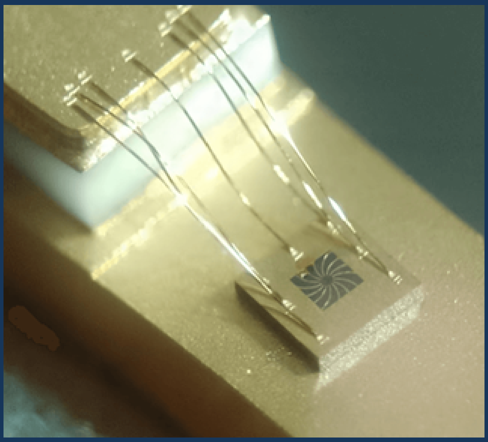


The source must also maintain frequency and power stability over wide temperature ranges and under mechanical stress, especially for airborne or orbital platforms. Ultimately, FSOC laser requirements balance optical power, spectral purity, modulation bandwidth, and environmental robustness, all while remaining eye-safe and tightly aligned to maximise photon efficiency across the channel.

PCSELS IN FSOC

A photonic crystal surface emitting laser (PCSEL) is a type of semiconductor laser that combines the advantages of photonic crystal engineering with surface emission. Unlike conventional edge-emitting lasers, which confine light within a waveguide and emit from the facet, PCSELs integrate a two-dimensional photonic crystal layer into the laser cavity. This layer acts as a highly efficient optical resonator and feedback mechanism, enabling coherent light emission vertically from the surface of the chip. The periodic photonic crystal pattern precisely controls the in-plane propagation and coupling of light, allowing single-mode operation over large areas and exceptional beam quality. As a result, PCSELs bridge the gap between high-power semiconductor lasers and precision beam control technologies.

PCSELs are highly advantageous for FSOC systems due to their ability to emit narrow, high-brightness beams with excellent beam quality and low divergence, which is critical for minimising signal loss over long distances. Unlike conventional laser sources, PCSELs combine the benefits of surface emission with single-mode output, enabling efficient coupling into free-space optics without the need for complex beam-shaping elements. Their high-power scalability makes them ideal for high-speed, high-reliability optical links. These properties position PCSELs as a next-generation laser source for compact FSOC systems in both terrestrial and space-based applications.



CURRENT TECHNOLOGY

For terrestrial and near-Earth links, distributed feedback (DFB) diode lasers at 1550 nm dominate because they are compact, energy-efficient, eye-safe at higher powers, and compatible with dense wavelength-division multiplexing (DWDM) telecom components. These are often paired with external modulators or built as electro-absorption modulated lasers (EMLs) to support 10s of GHz bandwidth. Terrestrial DFB and EML lasers, while compact and cost-effective, are limited in output power due to eye-safety regulations and thermal management, which restricts link range, especially under adverse weather conditions. Their spectral linewidths, though adequate for direct detection, are insufficient for high-order coherent modulation unless paired with costly external stabilization.

For very short links, such as indoor or chip-to-chip optical wireless interconnects, vertical-cavity surface-emitting lasers (VCSELs) at 850 nm are common due to their low cost, ease of fabrication in arrays, and high throughput in parallel links. VCSELs excel in short-range, parallel links but suffer from relatively high divergence and limited output power, making them unsuitable for long-distance FSOC. VCSELs struggle to be fabricated at longer wavelengths above 1055nm due to the material stacks causing delamination issues in fabrication which adds to the limitations of their uses in FSOC.

The next generation of FSOC lasers will need to combine high output power with narrow linewidths, ultra-stable frequency and intensity, and compact, energy-efficient packaging. Ideally, they should support multi-gigahertz modulation, be eye-safe at higher powers, and integrate seamlessly with adaptive optics for dynamic beam steering, enabling reliable high-data-rate links over long terrestrial or space distances even under challenging environmental conditions.

TABLE OF REQUIREMENTS

Parameter	Typical Requirement	Rationale	PCSEL justification
Operating Wavelength	850nm, 1310nm, 1550nm	1550 nm preferred (low attenuation, eye-safe, telecom components available).	PCSELs can be designed across the entire wavelength range. They have been demonstrated in 850nm, 1310nm, and 1550nm.
Output Power	10–500mW (terrestrial); up to several watts (space)	Higher power extends range and improves link margin. Limited by eye safety on Earth.	PCSELs scale power with area. Coherent arrays can be developed which allows for increased power output.
Beam Quality (M^2)	≈ 1 (near-diffraction-limited)	Ensures low divergence and efficient coupling into receiver optics.	The photonic crystal cavity enforces single-mode, spatially coherent emission, producing a nearly ideal gaussian beam with minimal divergence or higher-order spatial modes.
Spectral Linewidth	< 1nm (IM/DD systems)	Narrow linewidth reduces phase noise, critical for advanced modulation formats.	PCSELs have an inherently small spectral linewidth because their high-Q, small-volume cavities strongly confine light and suppress noise.
Relative Intensity Noise (RIN)	≈ −150dB/Hz	Minimises signal degradation, especially in coherent and high-order modulation.	The high-Q, single-mode photonic crystal cavity provides strong optical feedback and stable mode confinement.
Modulation Bandwidth	Up to 10s of GHz	Supports high-capacity (>100 Gbps) transmission.	The small photon lifetime (from strong optical confinement and efficient surface emission) and high differential gain enable fast carrier–photon dynamics and thus rapid intensity modulation. External modulators can also be used with CW high powered PCSELs to produce high modulation bandwidth.
Eye Safety Class	Class 1M (IEC/ANSI) for terrestrial applications	1550 nm allows higher launch powers while staying within safety limits.	PCSELs can be designed to hit specific class specifications.
Environmental Tolerance	Wide temp range (−40 to +85 °C), vibration resistant, shock resistant, solar heating resistant	Especially critical for aerospace and spaceborne FSOC terminals.	PCSEL provides strong optical feedback and a large mode–gain overlap, making a stable lasing mode across a large aperture.

SUMMARY

PPCSELs are emerging as a promising technology for FSOC emitters because they combine several key advantages in a single device. PCSELs produce highly coherent, narrow-linewidth beams with near-diffraction-limited divergence, which is critical for long-distance free-space links. They can be fabricated in large, scalable arrays, enabling high total optical power while maintaining excellent beam quality. As they are surface-emitting lasers, they have all the packaging and testing advantages that a VCSEL has, whilst being able to hit high power requirements in long wavelengths, similar to DFBs.

PCSELs can be engineered to emit at highly specific wavelengths, including eye-safe regions such as 1550 nm, enabling higher output powers without exceeding safety limits. Their combination of high power, excellent coherence, superior beam quality, and compact form factor makes PCSELs particularly well-suited for next-generation free-space optical communication systems.

Concept rendering of PCSEL embedded optical head of FSOC system being developed by Vector Photonics and Fraunhofer CAP

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