Free Space Optical Communications in Terrestrial & Satellite Systems with an InGaAs Quadrant Photodiode

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The earliest application of Free Space Optics (FSO) was with fire as the transmitter and the eye as the receiver in a line-of-sight (LOS) mission long lost to antiquity. The next advancement to Free Space Optical Communication (FSOC) led to using the sun as the transmitter and a mirror or shield to modulate the light to the eye as the receiver. This was a rudimentary communication system. Fast forward several millennia to 1880 and the *Photophone* patent awarded to Bell and Tainter for light communication between a transmitter (sun or carbon filament) and a receiver (selenium sensor). This is considered by many as the forerunner to Fiber Optics and Free Space Optical Communication. In the modern era, wireless terrestrial and satellite communications was based on RF transmission that put limits on bandwidth and security through limited frequency bands and open transmission paths. As developments in photonics advance its footprint into Free Space Optics and Free Space Optical Communication, terahertz transmission is within reach.

Terrestrial and satellite FSOC rely on both tracking and communication systems by utilizing bidirectional transmission between a transmitter and a receiver in a line-of-sight communication link. The Free Space Optics components typically operate in the short wave infrared (SWIR) spectrum with lasers, photodiodes, and avalanche photodiodes. This optical technology has allowed much higher data rates than RF transmission, achieving 10 to 100 times greater bandwidth. Another key advantage to optical transmission is the security made possible by the narrow laser beam widths. Many applications will use Wavelength Division Multiplexing (WDM) to facilitate optical link, two wavelength, bidirectional transmission to prevent optical crosstalk. This is done seamlessly within the optical interface. Although there are considerable differences between the data and tracking communication channels, beam alignment is the common metric.

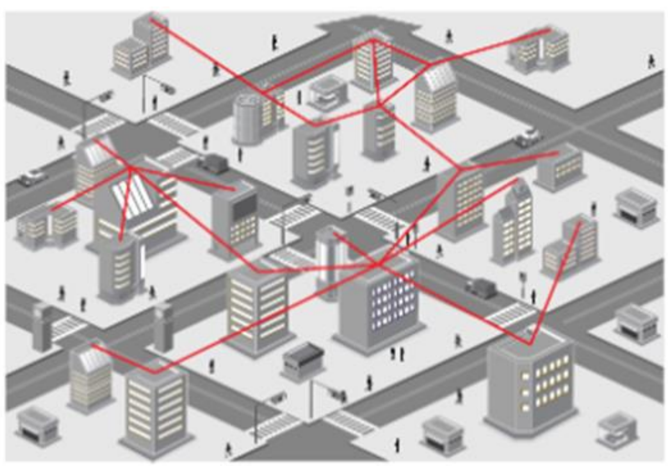

Figure 1: Short distance terrestrial FSOC campus[i]

Figure 1 illustrates a terrestrial FSOC system where discrete optical nodes are connected in a campus environment. Each node contains both optical transmitters and receivers.

The foremost requirement for any terrestrial optical bidirectional communication link is a continuous signal across the interconnected nodes. This beacon alignment system is in tandem with the laser communication channel allowing uninterrupted data communication. Terrestrial communication links operate both in short distance building-to-building or long-distance tower-to-tower LOS transmission. These can be impacted by physical instabilities and/or external vibration sources. Examples include building sway, thermal expansion and contraction, construction activities, rail or airport lines, or weather-related phenomena. Both short and long links are affected by atmospheric obscurants such as rain, fog, or snow that will absorb or scatter the incident laser transmitter channels thus reducing range by degrading the signal to noise ratio (SNR). Another consideration are intermittent beam blockages like bird flocks or insect swarms that can generate signal fade. Long distance terrestrial optical communication can be limited by the curvature of the Earth (tens of kilometers).

Figure 2: Satellite FSOC Constellation[ii]

Figure 2 illustrates an FSOC system where optical node satellites are connected in a constellation array.

The link distance for bidirectional satellite to satellite communications (Inter-Satellite Link) can be tens of thousands of kilometers for a line-of-sight link operation. Recent advances have been realized in NASA's "Laser Communications Relay Demonstration" to attain multi-gigahertz modulation with size, weight, and power (SWaP) saving across vast distances such as Earth to Moon and Earth to Planet bidirectional transmission. Low Earth Orbit (LEO) laser communications has greatly benefited from these advancements such as LEO communication networks and CubeSats. These SWaP CubeSat satellites (as small as 10 cm x 10 cm x 10 cm) are becoming ubiquitous in LEO to observe the earth and perform miniature experiments.

A critical component to any successful LEO operation is their orbital dynamics must be actively monitored to maintain LOS operation as different altitudes, velocity, atmospheric drag, or variations in Earth's gravitational field will degrade performance.

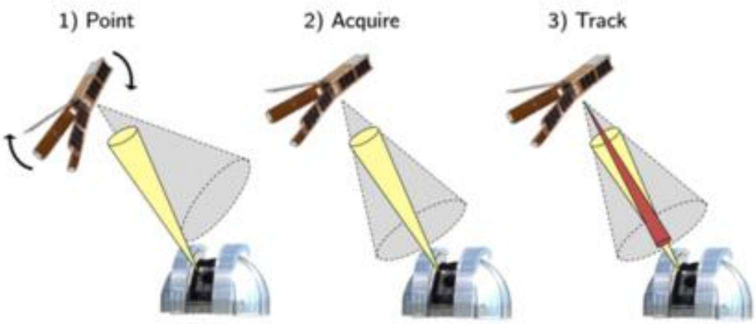

Figure 3: Point, Acquisition, and Tracking operating diagram[iii]

Figure 3 illustrates the PAT geometry between a satellite and a ground station or a satellite.

The principal tool to achieve and maintain optical alignment in a laser based terrestrial and satellite FSOC is the Pointing, Acquisition, and Tracking (PAT) algorithm.

Pointing is a course adjustment with the satellite beacon laser overfilling the receiving optics field-of-view (FOV). This begins the acquisition process. The ground station beacon laser or beacon satellite laser searches for the receiving satellite. This is an iterative process in the pointing phase. The ground station or beacon satellite transitions from primarily sensing as it attempts to acquire the beacon laser. Once the beacon is acquired, the transmit channel will overlap with the receiver channel. The final correction is the tracking phase so that the two satellites are aligned for communicating. The real time monitoring of the laser's spot position is the core technology to the laser beam control system, where the spot position detection accuracy determines the performance of the entire FSOC system.

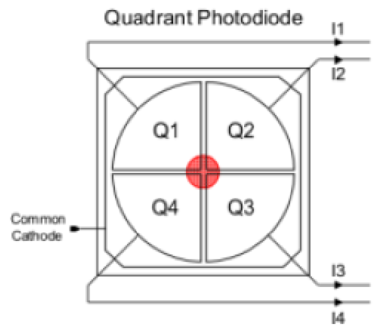

Figure 4: Quadrant Discrete Position Sensor[iv]

Figure 4 illustrates a quadrant position sensor vital to accurate and precise Free Space Optical Communication.

A quadrant photodiode (QPD) is a discrete position sensor. It has four photodiodes in a circular array with gaps between elements. The gap distance limits of the allowable spot size. Position sensing is achieved through ratio sensing between the four elements.

The QPD is the principal mechanism for maintaining the alignment that facilitates tracking between the transmitting and receiving satellites.

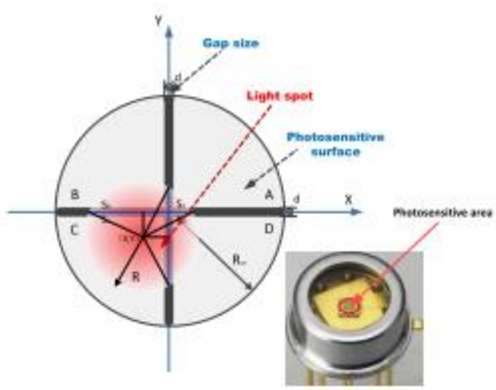

Figure 5: QPD schematic showing spot position[v]

Figure 5 illustrates the InGaAs quadrant photodiode graphic mounted in a TO-5 package optimized for the SWIR spectrum.

The quadrant sensor is a parallel circular array with four separate anode connections on a common cathode. Each quadrant sector is electrically isolated. The focused beacon beam is incident on the sensor. The position of the illuminated spot's centroid, determined by the output photocurrent of each sector, is processed into a two-dimensional location. The quadrant photodiode allows bidirectional transmission for continuous alignment.

The pointing, acquisition, and tracking mechanics achieve accurate beam alignment between transmitter and receiver ends thereby maintaining link connectivity.

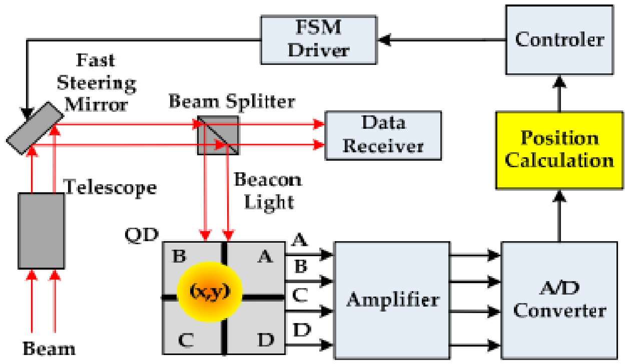

Figure 6: PAT block diagram illustrating feedback control with QPD[vi]

Figure 6 is a simplified PAT block diagram of a typical satellite terminal showing the beacon channel at 1300 nm.

A Fast Scanning Mirror (FSM) provides the acquisition/tracking function via a feedback mechanism. The input beacon signal is reflected off the FSM and a fraction reflected off the beam splitter into the QPD. This signal is processed into X-Y position coordinates by the QPD. This position data provides input into the FSM driver providing input to the FSM for alignment.

The key performance metrics for the PAT InGaAs quadrant photodiode is related to the electrical and optical characteristics for each sector:

- Sensitivity- Input power dynamic range operates from nW to mW.
- Surface Uniformity- Relative spectral responsivity between each sector is nearly 100%.
- Crosstalk- Sector to sector photocurrent leakage, or coupling, is less than 2%.
- Temporal Response- Nanosecond time constant.

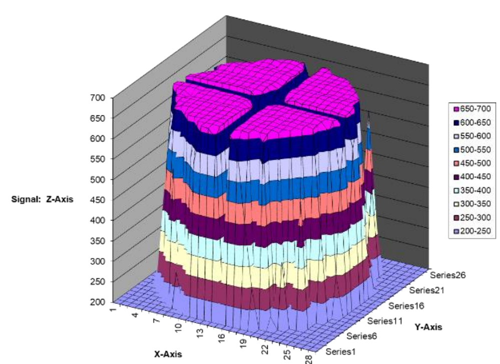

Figure 7: InGaAs QPD Surface Uniformity Profile[vii]

Figure 7 is a surface uniformity graphic showing the photo response across a typical GPD Optoelectronics InGaAs quadrant photodiode.

An incident 1550 nm spot (~10-micron diameter) was traversed across the X-Y axis generating a 3-D profile with the signal channel located on the Z-axis. This graphic shows the importance of sector uniformity to reduce requirements for any signal normalization in the amplification stages such as gain adjustments.

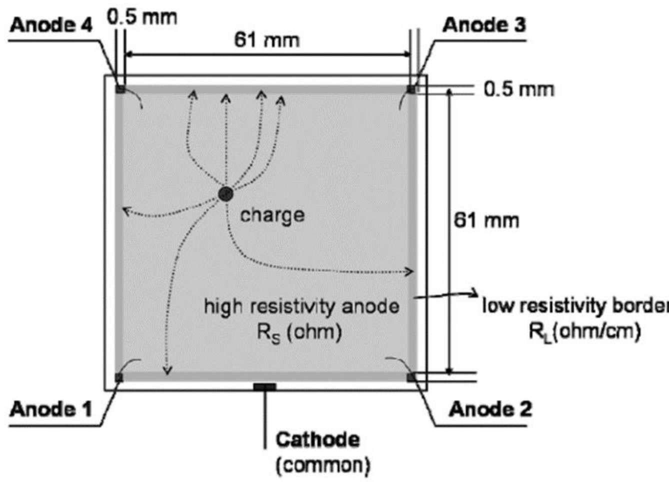

Figure 8: Silicon tetralateral continuous position sensing[viii]

Figure 8 illustrates an alternative optical position sensing technology.

There are two optical position sensing formats: discrete and continuous. The discrete measurements from a quadrant photodiode are the dominant metrics used in position, acquisition, and tracking. Continuous measurements are possible by using tetralateral photodiodes. The tetralateral design contiguously tracks beam in two dimensions without any gaps. These are ideal for tracking small spot diameters near tens of microns. However, it is limited in its modulation rate and noise performance due to its large area.

Summary

Terrestrial and Satellite Free Space Optical Communication system success is predicated on the pointing, acquisition, and tracking mechanisms to align multiple nodes in dynamic spatial/temporal systems. Successful PAT operation in point-to-point transmission is realized through the beacon channel InGaAs quadrant photodiodes.

As satellite-to-satellite laser communication constellations have become widespread in Low Earth Orbit, Medium Earth Orbit (MEO), and Geostationary Equatorial Orbit (GEO), precise bidirectional transmission becomes imperative. New and emerging technologies such as the CubeSat with their SWaT structure are readily serviced by quadrant photodiode miniaturization to facilitate laser bidirectional communications.

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[viii] "Performance evaluation of novel square-bordered position-sensitive silicon detectors with four-corner readout," A. Banu, Y. Li, M. McCleskey, M. Bullough, S. Walsh, C. A. Gagliardi, L. Trache, R.E. Tribble, and C. Wilburn, *Cyclotron Institute, Texas A&M University USA* and *Micron Semiconductor Ltd., UK*, 20 December 2007.