OPTICAL FREQUENCY GENERATION

UNLOCKING THE MILLIMETRE-WAVE AND SUB-THZ BANDS FOR SPACE, 6G MOBILE AND TEST AND MEASUREMENT

Executive Summary

Pilot Photonics has developed a flexible, accurate, and compact photonics integrated frequency generator, OFGU. It is a low profile module which uses an integrated optical comb laser and heterodyne techniques to generate ultra-stable, tunable RF carriers from 6 GHz to 220 GHz. OFGU replaces bulky electronic frequency-multiplier amplifier chains with a low-SWaP (size, weight, and power) photonic engine, delivering low phase noise, wide frequency agility, and seamless integration with optical networks. This paper explains the technology, highlights key application areas, and presents validation results showing readiness for 6G, test and measurement, and space markets.

While millimetre-wave (mm-Wave) and sub-terahertz (sub-THz) frequencies promise immense bandwidths and spatial resolution, access to such high-frequency bands remains limited by the maturity of traditional RF hardware. The projected new levels of performance in communications, sensing, and test systems are particularly restrained by limitations in frequency generation and conversion above 70 GHz. Optical techniques can help overcome these limitations by enabling direct generation and distribution of high-frequency signals with minimal loss and enhanced stability. Leveraging the inherent advantages of photonics, such as wide bandwidth, low noise, and efficient transmission over optical fibres, photonic methods provide a scalable and energy-efficient alternative to traditional electronic approaches. OFGU is the result of our commitment to realizing the possibilities of integrated photonics, one laser at a time.

1. THE GROWING DEMAND FOR HIGH-FREQUENCY BANDS

As data-hungry applications such as 8K streaming, AR/VR, and AI-enabled services proliferate, 5G-Advanced and 6G networks must achieve data rates beyond 100 Gb/s per cell site. This requires the use of wide channel bandwidths available only in the mm-Wave (30–100 GHz) and sub-THz (100–300 GHz) bands.

High frequencies also power next-generation radar, satellite links, and scientific instruments, but their deployment is constrained by hardware complexity. Electronic solutions rely on low-frequency local oscillators and frequency-multiplier chains, which introduce conversion losses, poor linearity, high power draw, and large physical size.

Optical technologies, by contrast, offer frequency-independent low loss, excellent phase stability, and the ability to distribute high-frequency signals over long fibre links. Pilot Photonics' OFGU leverages such advantages to simplify high frequency system architectures, and unlocks higher performance in applications including 6G mobile, space and defence, and high frequency test and measurement.

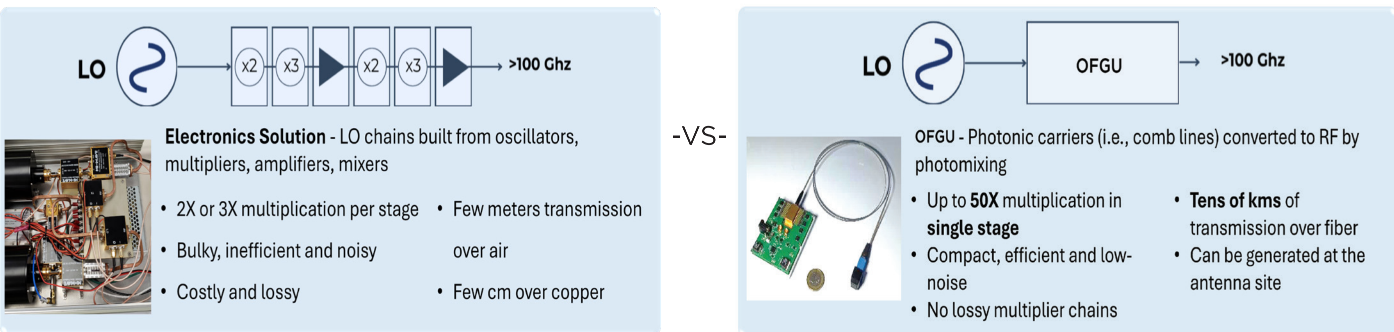

Figure 1 – Current electronics/RF solutions for >70 GHz TO carrier and signal generation vs the OFGU photonics solution.

2. MARKET DRIVERS AND USE CASES

2.1 Cellular and Wireless Backhaul

6G networks will combine ultra-wide bandwidths with distributed massive-MIMO architectures in order to achieve unprecedented data throughput, ultra-low latency, and high reliability for a diverse range of applications. 5G deployment in the 24–52 GHz band is gaining momentum, while 6G will use carriers above 70 GHz to access the wider channel bandwidths. Up to 25% of wireless deployment in some countries was based on 70/80 GHz E-band transceivers, and these will naturally transition to the W- (75-110 GHz) and D- (110-170 GHz) bands in the near future. However, under-developed hardware and short propagation distances at these frequencies (demanding dense deployment of antenna sites) remain the major hurdles to the wide deployment of such systems. Each remote antenna site must include compact, efficient RF hardware to drive deployment at large.

The OFGU's use of optical technology makes it an excellent choice to overcome these issues. It can be deployed either at the base station as an efficient, single-stage, agile local oscillator up to 220 GHz (frequency-generation mode) or at the central office (frequency-conversion mode), transmitting analog radio over fibre signals for simple remote up-conversion at the antenna site, as shown in Figure 2.Seamless integration of the OFGU unit with optical front-/backhaul distribution network enables the simplest base-station design, bringing high-frequency signals closer to end users. This centraliszation of resources enables the wide deployment of remote antenna sites. Due to its manufacturing scalability, such deployment can proceed at a fast, cost-efficient rate.

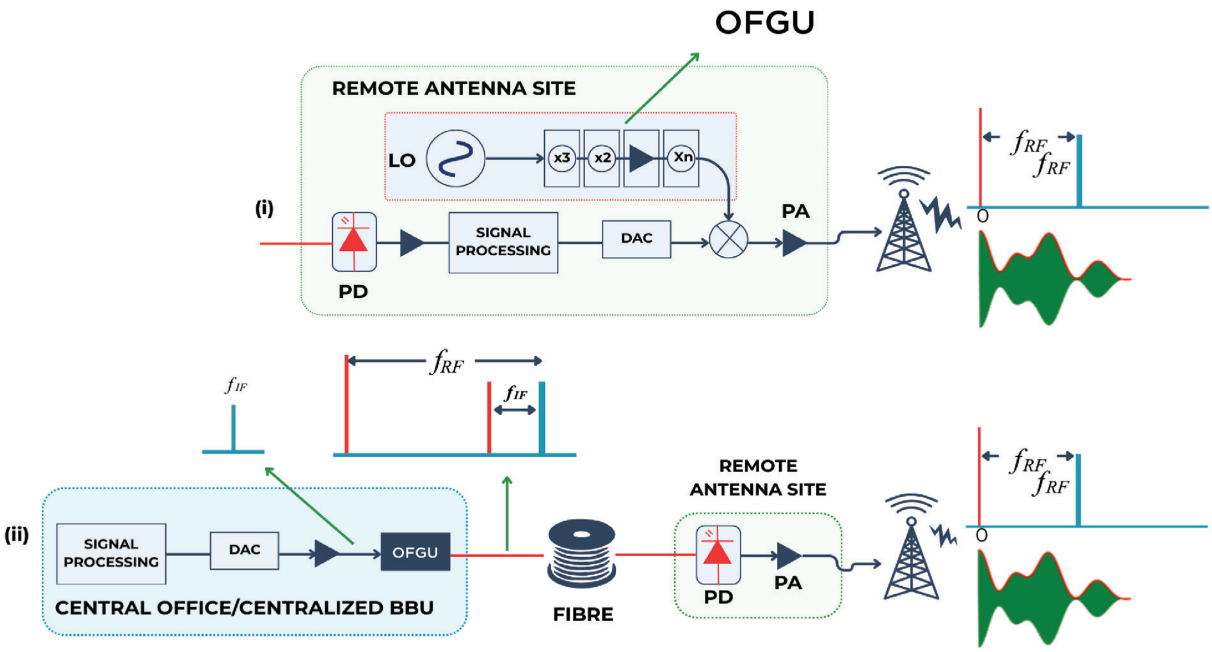

Figure 2 – (i) Remote Antenna Base Station Architecture showing OFGU in frequency generation configuration replacing the RF chain consisting of local oscillator and multipliers, and (ii) Integrated optical fronthaul and remote mmWave/sub-THz signal generation facilitated by OFGU in frequency conversion configuration.

2.2 Space and Defence

The proliferation of satellite constellations and the emergence of non-terrestrial networks (NTN) have increased interest in the use of high-frequency feeder links and on-board frequency conversion in next-generation satellites. Traditional coaxial distribution of local oscillator signals contributes significant mass, with GEO payloads requiring more than 40 kg of coaxial cable. Fibre distribution made possible by OFGU can decrease this mass by over than 80% while delivering agile RF generation for all of the satellite communication bands from a single frequency generation unit. Pilot Photonics has supplied early OFGU units to a European satellite manufacturer and is currently developing radiation-tolerant flight models.

2.3 Test and Measurement

Test and measurement equipment for high-frequency applications must consistently remain at the forefront of technological advancement. This necessitates that T&M vendors continually innovate, introducing new technologies and methodologies to advance equipment standards. Characterisation of high data-rate optical and 6G components and systems requires instruments capable of operating well above 70 GHz. Existing solutions often rely on separate, band-specific electronic extenders, which can result in variable noise characteristics and increased cost, size, and complexity. OFGU offers a comprehensive solution by providing a single broadband, low-noise generator, facilitating reliable and repeatable testing from 6 GHz to 220 GHz while reducing instrument size, weight, power consumption, and cost (SWaP-C).

3. OFGU AND HOW IT WORKS

At the heart of OFGU is Pilot Photonics' gain-switched comb laser, monolithically integrated with injection-locked filtering on a single InP photonic integrated circuit (PIC) and integrated with a high-speed photodiode.

1. A low-frequency RF drive modulates the laser, producing a coherent optical frequency comb. Pilot Photonics' patented 'gain-switching' technique yields high coherence, low linewidth RF carriers, enabling it to outperform external cavity lasers (ECLs), fibre, and integrated dual-laser approaches.
2. The active demultiplexer selects two comb lines spaced by the desired mm-Wave/Sub-THz frequency.
3. When these two tones beat on the photodiode, they generate a high-purity RF carrier equal to their frequency separation.

This optical heterodyne process converts optical precision into RF stability, enabling wide-range tunability and ultra-low phase noise.

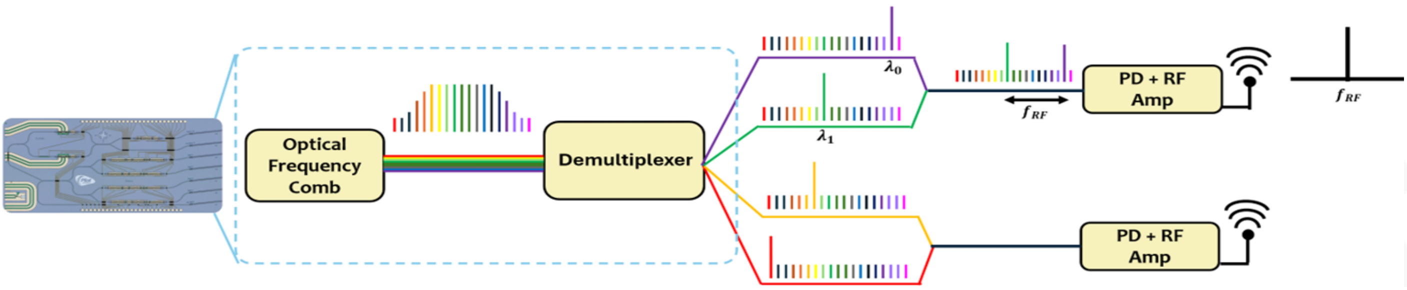

Figure 3 – OFGU-6G concept illustration: optical frequency comb generates equally spaced optical carriers: on-chip the demultiplexer can select any two carriers spaced by the desired mm-Wave frequency. The two optical carriers can then be photodetected to produce the mm-Wave carrier/signal via heterodyning.

All optical functions (comb generation, active demux, VOAs, SOAs, and splitters) are monolithically integrated on a single InP photonic integrated circuit. This single-chip solution eliminates hybrid-integration losses, enhances stability, and supports high-volume manufacturing. The fabricated PIC and its complete package are shown in Figure 4.

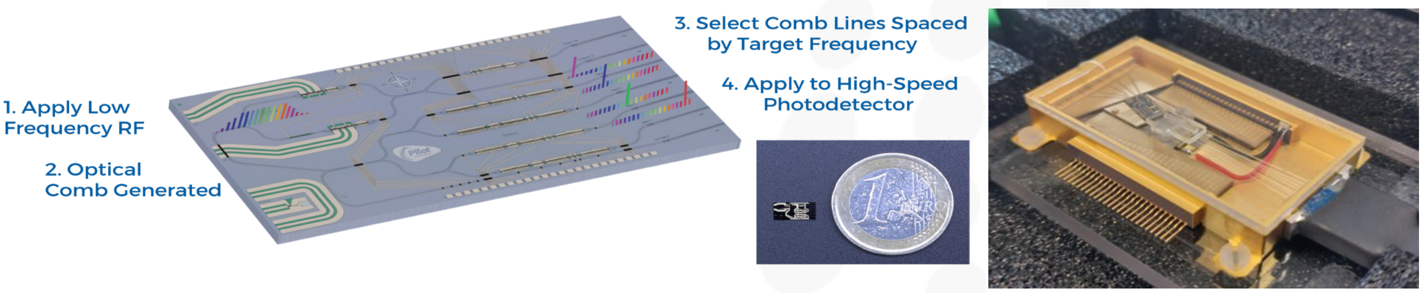

Figure 4 – The functions of comb generation and injection-locked filtering/demultiplexing are integrated, with a high-speed photodetector for optical heterodyning, onto a single, tiny PIC. This configuration enables up to x50 multiplication in a single stage. The PIC is currently packaged in a large-area, and further miniaturization is underway.

4. UNIQUE SELLING POINTS AND KEY BENEFITS OF OFGU

For high-precision distance measurement, the iCLA provides a dual comb architecture that generates two phase-locked optical frequency combs with tunable repetition frequencies. The combs can be used in a Michelson interferometre configuration to measure distances with exceptional accuracy, overcoming the limitations of periodic ambiguity that affect traditional interferometric methods. In measurement using discrete components, an accuracy of 12 μm over distances up to 2.5 metres is achieved, with robust performance across different environmental conditions. This makes the OFGU ideal for applications in manufacturing, robotics, and autonomous vehicles (Figure 3). More details can be found in Further Reading [iii]

Feature	What It Delivers	Why It Matters
Photonic RF Generation	Optical heterodyne replaces electronic multiplier chains	Lower loss, reduced EMI, compact architecture
Optical Frequency Comb	Whilst free-running lasers produce uncorrelated lines, the comb generates phase-correlated lines.	Correlation enables frequency stable and low phase noise (PN) RF carriers generation
Low Phase Noise (PN) and High Stability	Comb lines exhibit fixed frequency spacing and are phase-locked	Enables advanced modulation and low-jitter operation
Active Demultiplexing	Tunable selection of comb lines	Broad frequency agility (6–220 GHz) in one device
Monolithic InP PIC	Integrated lasers, amplifiers, VOAs on a single PIC	High reliability, manufacturable at scale
Low SWaP-C Design	Miniaturized PCB assembly	Smaller, lighter, lower-power modules
Optical Network Compatibility	Direct integration with optical front/backhaul	Centralised architectures, remote RF generation
Broadband Conversion Capability	Mach–Zehnder modulator enables up-conversion	Replaces the entire RF chain for frequency translation

5. PERFORMANCE AND FORM FACTOR

OFGU is delivered in a compact PCB assembly, integrating all photonic and electronic functions on a single credit card-sized module. Measured results have shown broadband carrier generation from 6 GHz to 162.5 GHz with phase-noise performance meeting telecom and radar specifications. A 44 GHz carrier delivered to a space prime contractor achieved <–105 dBc/Hz at 100 kHz offset. D-band operation from 125 GHz to 162.5 GHz has been generated along with optical up-conversion of intermediate-frequency data to 150 GHz.

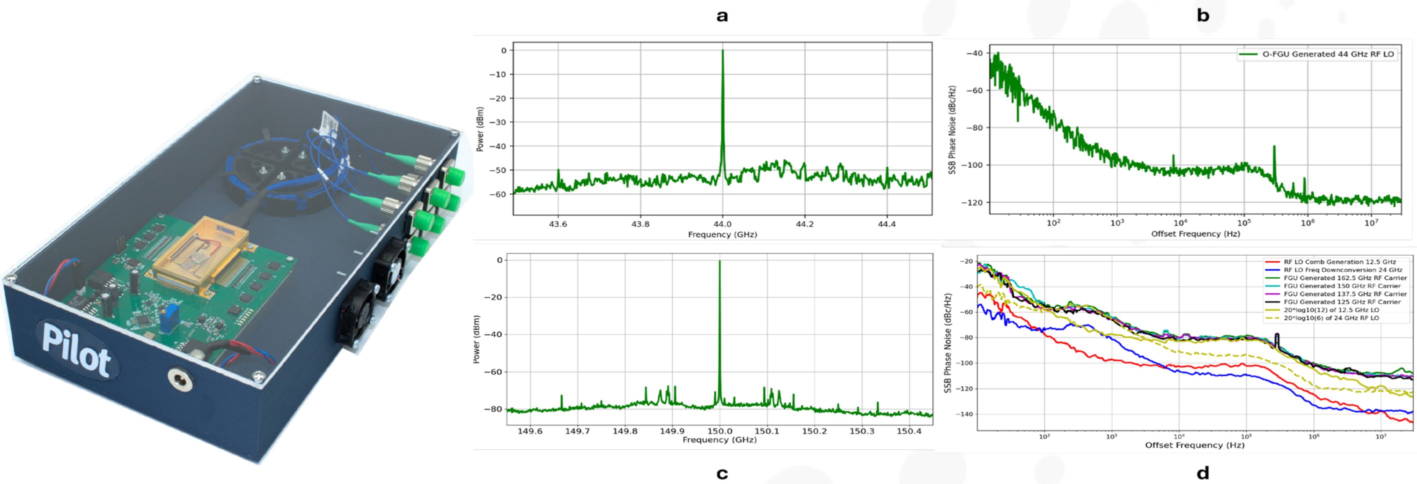

Figure 5 –(Far left) Image of the OFGU unit with a credit card-sized PCB and 52-pin packaged PIC assembly; spectrum (top centre) and phase noise (bottom centre) of the 44 GHz carrier; spectrum (top right) and phase noise (bottom right) of the 150 GHz RF carrier generated from the OFGU unit.

6. MARKET OUTLOOK

The shift to 6G and sub-THz systems is driving rapid growth in compact high-frequency RF sources and frequency multipliers. The combined total market for the RF oscillator and frequency multiplier was around $36.70 billion in 2024 [iii,iv] and is projected to exceed $83.51 billion by 2033 due to the growing demand for higher data rates in communication systems and higher resolution in measurement systems.

As OEMs prioritize SWaP reduction and centralized architectures, integrated photonic generation is positioned to augment or replace traditional electronic designs and establish a new standard for wideband RF front-ends. Electronic multiplier chains face efficiency and phase-noise limits above 70 GHz, while laboratory optical sources remain bulky and costly. Pilot Photonics' OFGU bridges this gap by providing a monolithic photonic solution that is manufacturable at scale. OFGU delivers laboratory-grade performance in a small form factor, deployable in the field, at volume.

7. CONCLUSION AND NEXT STEPS

OFGU combines Pilot Photonics' gain-switched comb technology, injection-locked optical filtering, and integrated photodetection to generate tunable, low-noise carriers up to and beyond 200 GHz. It offers a compact, energy-efficient alternative to electronic frequency-generation chains for 6G, instrumentation, and space applications.

For ***mobile network infrastructure designers***, the OFGU reduces radio-unit complexity, power, and cost while supporting optical fronthaul integration.

For ***test and measurement vendors***, it provides a single broadband source with consistent noise performance.

For ***space and defence primes***, it enables lightweight fibre-based RF distribution and high-frequency conversion with proven stability.

Across all markets, OFGU merges optical precision with RF functionality, creating a unified approach to wideband frequency generation and distribution.

Interested organisations can gain early access to the OFGU technology through our evaluation programme by contacting **sales@pilotphotonics.com**

REFERENCES

i. https://www.ericsson.com/en/reports-and-papers/mobility-report/reports/june-2025
ii. https://datahorizzonresearch.com/rf-oscillator-market-20336
iii. https://datahorizzonresearch.com/rf-frequency-multiplier-market-20316
iv. https://www.grandviewresearch.com/industry-analysis/global-telecom-services-market