Our Ultimate Fiber Network Just Got a New Look with a Comb

A Comprehensive Exploration of Optical Frequency Combs

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1. Introduction

Optical frequency combs have garnered significant attention in recent years for their transformative potential on how optical communication networks could evolve. Leveraging cable's fiber access topologies in particular, these unique light sources can provide our industry with a competitive advantage through a common lower-cost optical signal generator for all optical systems. Optical frequency combs are characterized by optical wavelengths with equal frequency spacing and phase coherence, eliminating the need for guard bands between channels and individual wavelength frequency control, allowing operators to densely pack optical carriers. This increased spectral efficiency can help maximize the use of existing fiber infrastructure. [1]. Other benefits include reduced transceiver power consumption and improved system performance through system-level integration and signal processing. The advantages of optical frequency combs are evident in both dense wavelength division multiplexing (DWDM) transmitters and receivers. In transmitters, a single comb generator can replace multiple discrete distributed-feedback(DFB) lasers or external cavity lasers (ECL), simplifying system design and reducing costs. On the receiver side, using a comb as the local oscillator facilitates joint digital signal processing, which in turn reduces receiver complexity and increases phase noise tolerance. These improvements lead to more robust and reliable communication systems. Furthermore, the deployment of frequency combs at network hubs opens up new possibilities for wireless communication. Through photodetection, these combs enable the generation of low-noise millimeter-wave signals. This capability simplifies radio design, provides access to multiple wireless bands with wide bandwidths, and paves the way for true convergence between wired and wireless networks.

This work outlines a comprehensive exploration of optical frequency combs and their potential to revolutionize optical networks. It begins by introducing the concept of the Optical Grid, which aims to optimize optical resource utilization in future optical networks. The optical frequency comb is presented as an Optical Power Generator, analogous to electrical power generators in the electrical grid, capable of simultaneously generating multiple optical carriers, where optical carriers are generated in bulk as a basic good tool which are then used as input to or within a diversity of systems. We then delve into the technical aspects of frequency combs, discussing their representations in both time and frequency domains. We highlight the key parameters used to evaluate comb line performance, providing a foundation for understanding their capabilities and limitations. The paper proceeds to describe various methods for generating optical frequency combs, including microresonator-based, electro-optical modulation-based, and quantum dot laser-based approaches that we developed. Each method is presented in certain detail, offering insights into their operational principles and unique characteristics.

To demonstrate the practical applications of these comb sources, the paper presents an experimental result: the transmission of up to 50 Terabits per second over a single access network fiber. This showcases the immense potential of frequency combs in dramatically increasing network capacity. Furthermore, the paper introduces a converged optical-wireless DWDM access network architecture. This innovative approach enables the simultaneous delivery of coherent optical signals and millimeter-wave/CBRS signals over both fiber and wireless links, illustrating the versatility of frequency comb technology. The final part of the message addresses the challenges associated with integrating frequency combs into existing cable communication networks. We also provide insights into potential solutions and migration strategies, aiming to guide the industry towards an advanced cable fiber network infrastructure that fully leverages the benefits of optical frequency combs. Our cable fiber access networks which follow a hub and spoke topology are particularly suitable to efficiently leverage a single centralized optical source capable of generating multiple carriers. It avoids the replication of multiple discrete sources that are used in conventional point-to-point links with all their associated cost-complexity. Optical frequency combs maximize operators' fiber infrastructure investment as it cost effectively fills the fiber strands with high fidelity optical carriers suitable for communications, sensing, backhauling and many other applications.

2. The Vision of Optical Grid

In the current digital age, broadband connectivity has undergone a significant transformation, shifting from a luxury to an essential utility that has fundamentally changed how individuals, businesses, and institutions operate and interact. It has now attained the status of critical infrastructure [2], comparable to electricity or water, as it supports a wide range of daily activities across diverse user groups. Our cable networks play a vital role as the central nervous system of this interconnected world. They serve as the crucial conduit that connects a vast and varied ecosystem of endpoints, including data centers, wireless access points, enterprises, and residential customers. The diverse requirement of users and use cases presents a formidable challenge for cable network operators. The main challenge lies in efficiently meeting the diverse and often conflicting service requirements and consumption patterns of such a varied user base. For example, a data center may require ultra-high bandwidth and extremely low latency for real-time applications, while an IoT device might prioritize energy efficiency and reliable, albeit low-bandwidth, connectivity. Similarly, a residential user may demand high-speed downloads for streaming and consistent performance for video calls, while an enterprise may prioritize guaranteed uptime and security features.

However, current network design paradigms have not fully adapted to this complex reality. These designs are primarily optimized for top-tier services and often adopt a one-size-fits-all approach, offering limited flexibility in resource allocation and service provisioning. This rigidity can lead to inefficiencies, where high-capacity resources are underutilized for some users, while others experience suboptimal performance. These limitations become particularly apparent during peak usage times when network resources are strained across all user segments, rapidly changing usage patterns like those seen during global events such as the COVID-19 pandemic, and the introduction of new technologies or services that require different network characteristics. This challenge also presents an opportunity for innovation in network design. Technologies such as artificial intelligence can be incorporated for predictive resource allocation, software-defined networking can provide greater flexibility, and edge computing can reduce latency for certain applications. The goal is to create a more responsive, efficient, and equitable broadband ecosystem that can truly serve as the foundation for our increasingly digital society.

For such future network design, we propose a paradigm shift towards a more adaptable, scalable, and cost-effective network architecture: the Optical Grid. Drawing inspiration from the electrical power grid's on-demand nature, this novel approach aims to provide network capacity with unprecedented flexibility, allowing subscribers to access the bandwidth they require precisely when needed. As illustrated in Figure 1 (a), the electrical grid starts at power plants, where generators produce electricity. This electricity is then stepped up to very high voltages by transformers and sent over long-distance transmission lines. At substations closer to populated areas, the voltage is stepped down. From there, distribution lines carry electricity at lower voltages to end users like homes and businesses.

The electrical grid and broadband access networks share several key features and similarities. Both systems provide resources instantly when needed, with electricity immediately available at the flip of a switch and broadband delivering data promptly upon accessing online services. These networks are designed for scalability, handling varying loads from low to high demand. They adapt flexibly to changing user needs, managing fluctuations in power or bandwidth requirements throughout the day. As essential utilities, both electricity and broadband are expected to be ubiquitous, available wherever and whenever needed. They rely on extensive physical infrastructure to deliver services to end-users. Future broadband networks, like the electrical grid, are envisioned to dynamically allocate resources, expanding or contracting capacity based on current needs.

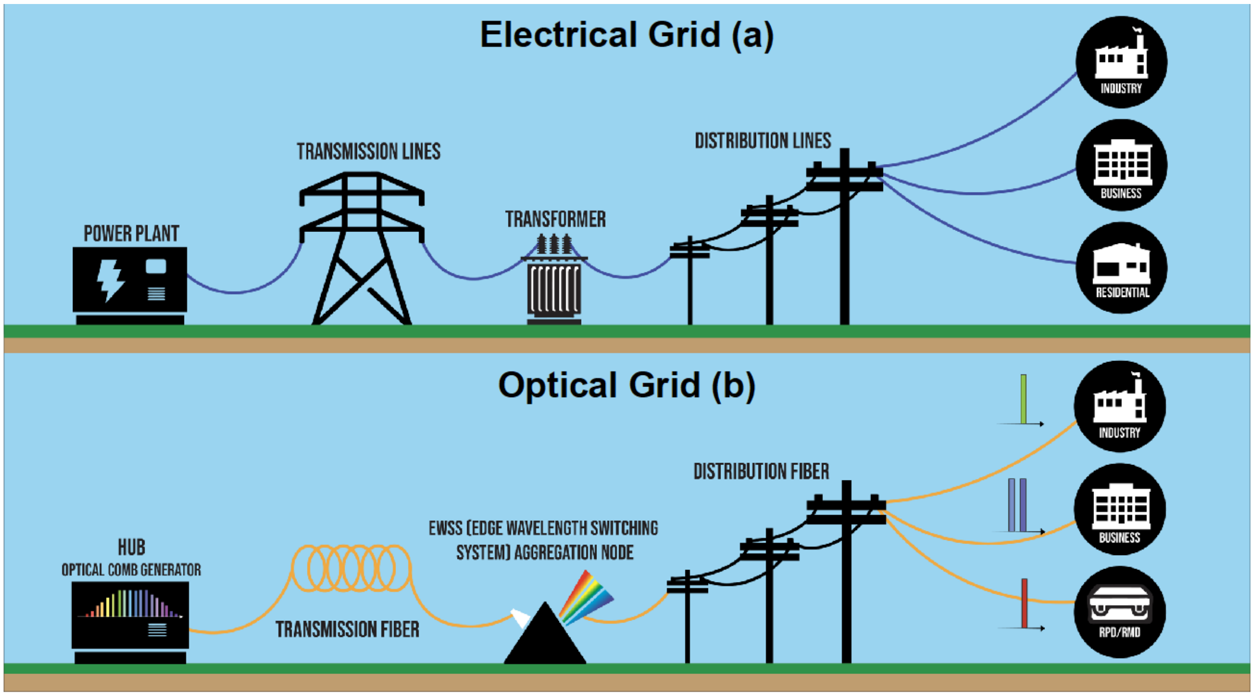


Figure 1 – Similarities of Optical Grid Vision with Electrical Grid

The Optical Grid begins at hubs, where optical signal generators produce light signals carrying data, as illustrated in Figure 1 (b). These signals are then transmitted over optical fibers, analogous to electrical transmission lines. At aggregation nodes, edge wavelength switching systems (EWSS) [3-4] perform a role similar to transformers in the electrical grid. They provide wavelength-granularity control, allowing for efficient switching and distribution of optical signals. From these nodes, distributed fibers carry different wavelengths of light to end users, much like how electrical distribution lines carry power to homes and businesses. The Optical Grid concept leverages multiple optical wavelength sources as the foundation for future access infrastructure. This innovative approach promises to dramatically reduce the cost per bit while enhancing the network's ability to support a wide range of services on-demand. A significant feature of the Optical Grid is its capacity to efficiently carry both wired and wireless transmissions within a converged network architecture, marking a crucial step towards true network convergence. The implementation of edge wavelength switching systems brings us closer to the goal of delivering individual wavelengths—distinct colors of light—to each network endpoint. This granular control and resource allocation capability opens up new possibilities for customized service delivery and efficient network management.

Central to realizing the Optical Grid vision is the development of an efficient optical power supply, analogous to the electrical power generators that fuel the electrical grid. The optical frequency comb serves this crucial role, functioning as the optical power supply for the future Optical Grid. This technology represents a quantum leap in optical carrier generation, capable of simultaneously producing hundreds, potentially even thousands, of synchronized information optical carriers from a single transmitter source. The optical frequency comb’s ability to generate multiple synchronized carriers from a single source not only enhances the efficiency and scalability of optical networks but also paves the way for unprecedented flexibility in bandwidth allocation and service delivery. This technology has the potential to revolutionize how we think about and implement our network infrastructure, our data centers and optical systems, offering the promise of more robust, flexible, and efficient communication systems for the future.

The Optical Frequency Comb is a central focus of this article. The subsequent content will concentrate on various comb sources, their primary applications in future network communications, and the challenges and migration strategies faced in moving from laboratory experiments to field deployments. This exploration will provide insights into how Optical Frequency Comb technology is poised to transform network infrastructure and communications systems, addressing both the potential benefits and the practical considerations of implementing this innovative technology on a large scale.

3. What is an Optical Frequency Comb

An optical frequency comb provides a number of precisely spaced and equidistant spectral carriers generated by a single device or subsystem, as illustrated in Figure 2. The individual spectral components, commonly referred to as 'comb lines,' are characterized by their precise and uniform spacing in the frequency domain. This equidistant nature of the comb lines is a key feature that makes optical frequency combs valuable for various applications in metrology, spectroscopy, and telecommunications. A crucial property of these comb lines is their strong phase correlation. This means that the phase relationships between different comb lines are well-defined and stable over time. This phase coherence is maintained across the entire comb spectrum, which can span hundreds of nanometers in wavelength or hundreds of terahertz in frequency [5].

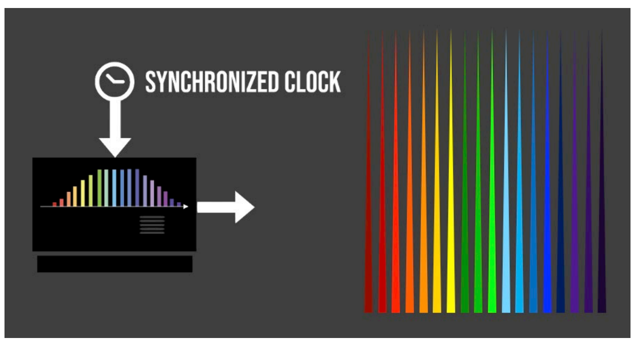


Figure 2 – Illustrating an Optical Frequency Comb Generation

Optical frequency combs have distinct representations in both the time and frequency domains:
In the time domain, an optical frequency comb appears as a train of ultrashort pulses. This representation is characterized by regularly spaced pulses in time, with pulse durations typically in the femtosecond range, a constant time interval between pulses (inverse of the repetition rate), and pulse-to-pulse phase evolution determined by the carrier-envelope offset frequency. The electric field of the pulse train can be described as:

$$E(t) = A(t) * \exp\left(i(2\pi f_c + \varphi_{CE})\right) * \sum \delta(t - nT) \qquad (1)$$

where $A(t)$ is the pulse envelope, f_c is the carrier frequency, φ_{CE} is the carrier-envelope phase, T is the time interval between pulses, and δ is the Dirac delta function.

In the frequency domain, an optical frequency comb appears as a series of equally spaced, narrow spectral lines. The key features of this representation include evenly spaced spectral lines, constant frequency spacing between adjacent lines (repetition rate), a wide spectral range often spanning hundreds of terahertz, and a well-defined phase relationship between comb lines. The frequency of each comb line can be described by the equation:

$$f_n = f_0 + n * f_{rep} \qquad (2)$$

where f_n is the frequency of the nth comb line, $f_0$is the carrier-envelope offset frequency, f_{rep} is the repetition rate from the microwave domain to the optical domain, and n is an integer. Equation (2) is referred to as the comb equation.

The frequency and time domain representations are related through the Fourier transform, with the evenly spaced spectral lines in the frequency domain corresponding to the periodic pulse train in the time domain (the repetition rate f_{rep} is the inverse of the pulse-to-pulse timing T). Experimentally speaking, real implementations of pulse trains are not ideal impulse responses but ultrashort pulses with a certain pulse width and thus, the equivalent optical frequency combs are not infinite, but limited in bandwidth.

Optical frequency combs have revolutionized numerous scientific and technological fields with their diverse applications. In precision spectroscopy, these combs enable highly accurate measurements of atomic and molecular spectra, advancing research in chemistry and physics. The development of optical atomic clocks has been transformed by frequency combs, resulting in timekeeping devices that surpass traditional atomic clocks in accuracy. In metrology, these combs act as precise rulers for measuring optical frequencies, wavelengths, and distances. Astronomers use frequency combs for calibrating spectrographs, enhancing the precision of instruments used in exoplanet detection and cosmic phenomena studies. LIDAR and remote sensing technologies have seen improvements in accuracy and range thanks to frequency combs, with applications extending to autonomous vehicles and environmental monitoring. In the medical field, these combs have enabled new techniques in biomedical imaging, particularly in optical coherence tomography. Ultrafast science has been advanced by frequency combs, allowing researchers to study extremely rapid physical and chemical processes.

The research outlined in this report is to explore and analyze the application of optical frequency combs in MSO communication networks. Optical frequency combs have emerged as a promising technology with the potential to revolutionize various aspects of telecommunications, including signal generation, data transmission, network convergence, and the vision of Optical Grid. For optical combs to be effectively integrated into communication networks, they must satisfy a set of stringent technical requirements. Optical frequency combs are characterized by several key parameters that determine their performance and suitability for various applications, particularly in communication networks. As illustrated in Figure 3, these parameters include:

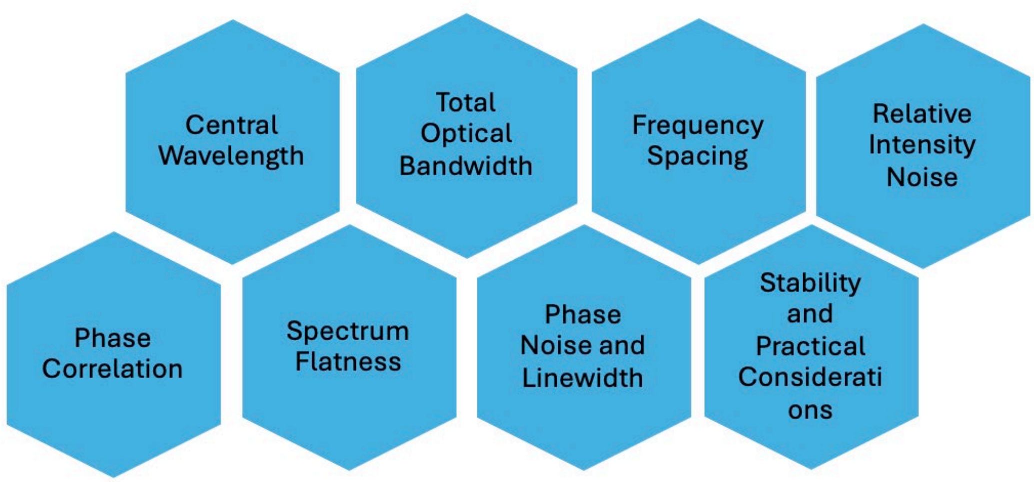


Figure 3 – Key Parameters of Optical Frequency Combs

- Total Optical Bandwidth: This represents the total width of the optical spectrum produced by the comb, also known as frequency span. It determines the maximum number of available comb tones, directly influencing the system's transmission capabilities.
- Spectrum Flatness: This parameter describes the uniformity of optical power across different comb tones. A flat-top power distribution is preferable in communication applications as it minimizes the need for equalization and ensures consistent performance across channels.
- Frequency Spacing: Also referred to as Free Spectral Range (FSR), this is the frequency interval between adjacent comb lines.
- Central Wavelength: This denotes the wavelength of the central comb tone in the comb spectrum.
- Relative Intensity Noise (RIN): This quantifies the intensity noise (optical power fluctuations) normalized to the average power level. These fluctuations in intensity, phase, and frequency are caused by spontaneous emission in the laser cavity.
- Phase Noise and Optical Linewidth: These interrelated parameters are crucial for advanced modulation formats that encode information in the carrier phase. Spontaneous emission produces random phase fluctuations, resulting in phase noise, which is equivalent to frequency variations.
- Phase Correlation: This measures how well the phase noise of different comb lines correlates. It's typically assessed by detecting the optical comb with a high-speed photodiode and observing the linewidth of the resulting radio frequency (RF) beat tone.
- Optical Power per Comb Line: Higher power per comb tone can eliminate the need for bulky and costly optical amplifiers in transmitters, potentially increasing transmission range and reducing system cost and power consumption.
- Stability and Practical Considerations: Long-term stability in wavelength, frequency spacing, and optical power is essential for reliable operation. Additionally, power consumption, compactness, manufacturing costs, and reproducibility are key factors driving the commercial viability and deployment of optical frequency combs in communication systems.

These parameters collectively determine the performance and applicability of optical frequency combs in various communication network scenarios and are crucial considerations in the design and implementation of optical communication systems and networks with the use of optical frequency combs.

4. How Does an Optical Frequency Comb Work

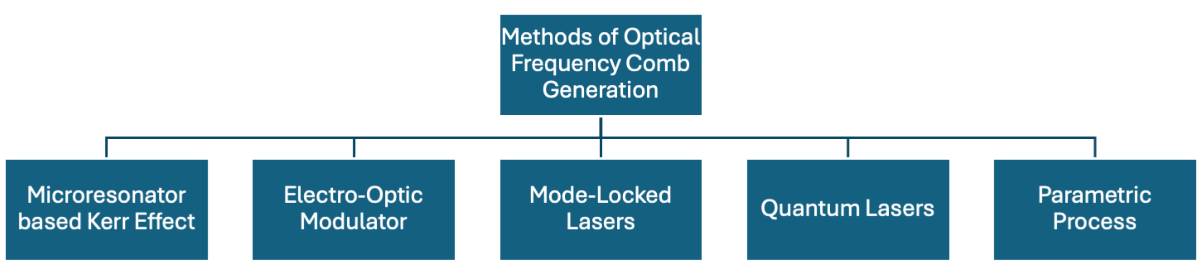


Figure 4 – Different Generation Methods of Optical Frequency Combs

As illustrated in Figure 4, optical frequency combs can be generated through several methods, each with its own advantages and challenges. Microresonator-based combs utilize nonlinear optical effects in high-Q cavities to generate broad spectra from a single pump laser. Electro-optic modulation offers another technique, where a continuous-wave laser is modulated to create sidebands that form the comb. Mode-locked lasers, particularly those based on titanium-sapphire or fiber technologies, are a common approach, producing a series of equally spaced spectral lines. Quantum cascade lasers can directly emit frequency combs in the mid-infrared region. Additionally, different frequency generation and parametric processes in nonlinear crystals can be employed to create combs in various spectral regions. Each method offers different characteristics in terms of spectral coverage, line spacing, and stability, allowing researchers to choose the most suitable approach for their specific applications.

This research work will demonstrate three methods for designing comb generation systems. The focus will be on microresonator-based comb generation, electro-optic modulation techniques, and quantum dot lasers. The study will delve into the underlying principles and experimental setups. By exploring these diverse approaches, the research aims to provide an overview of current technologies in optical frequency comb generation, highlighting their respective strengths in the field of photonics and telecommunications.

4.1. Microresonator based Kerr Comb Generation

The fundamental principle of microresonator-based comb generation relies on the interaction between intense laser light and nonlinear optical materials within a small, highly confining cavity. As illustrated in Figure 5(a), when a continuous-wave (CW) laser is coupled into the microresonator (a high-quality-factor (high-Q), it circulates and builds up high optical power. This intense field interacts with the nonlinear medium, typically through processes like four-wave mixing (FWM), leading to the generation of new frequency components. As these components continue to interact, they create a cascade of equally spaced frequency lines, forming an optical frequency comb. Microresonator-based comb generation is renowned for its capacity to produce compact, efficient, and broad-spectrum frequency combs. Recent research has focused on developing chip-scale comb sources using microresonators, commonly referred to as microcombs. These innovations aim to significantly reduce the size, weight, and power consumption (SWaP) of devices while facilitating system-level integration, potentially revolutionizing the field. Microcombs have been successfully implemented in various integrated photonic platforms, notably silicon and silicon nitride (SiN). Silicon carbide (SiC) has recently emerged as a promising material for microcomb generation, owing to its strong Kerr nonlinearity—estimated to be four times that of SiN, as shown in Figure 5(c). This property allows for a substantial reduction in required optical power, potentially exceeding an order of magnitude under comparable conditions. The development of low-loss SiC-on-insulator (SiCOI) device platforms has further advanced the field, enabling the realization of single solitons and octave-spanning microcombs. These advancements underscore the potential of SiC-based microresonators in pushing the boundaries of microcomb technology [6].

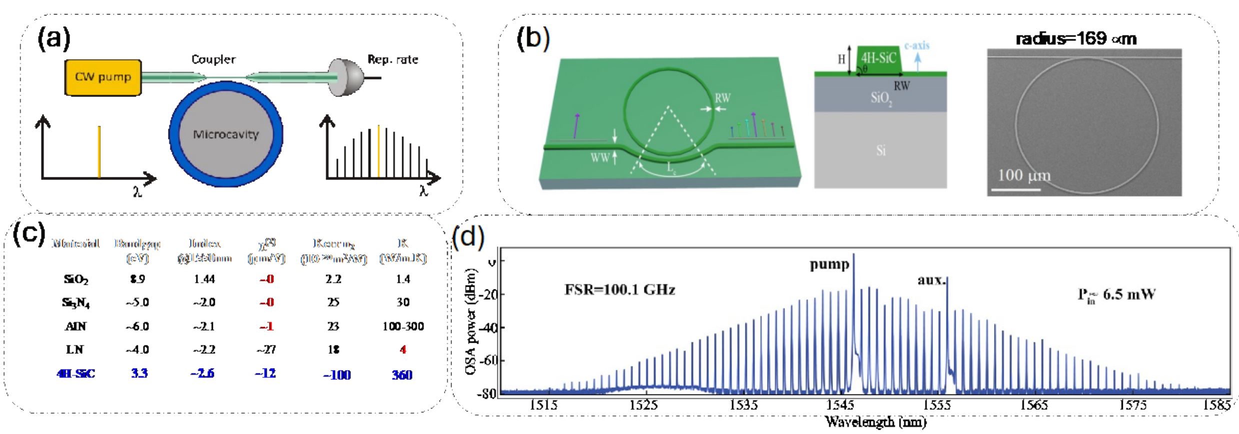


Figure 5 – Microresonator based Comb Generation: (a) Experimental Setup, (b) Schematic Design based on Silicon Carbide (SiC), (c)Different Material Property Comparison, (d) Optical Spectrum with on-chip 6.5mW Pump Power

The fabrication process for the silicon carbide-on-insulator (SiCOI) wafer utilized a bonding and polishing method, resulting in a structure comprising a 700-nm-thick layer of 4H-SiC atop a 2-mm-thick oxide layer. This configuration was employed for the devices developed in this work. Through the application of optimized nanofabrication techniques, including electron-beam lithography and plasma etching, we were able to precisely create low-loss photonic components such as waveguides and microresonators. An example of the fabricated SiC microrings is depicted in Figure 5(b). The ring radius was specifically chosen to be 169 µm, a dimension that results in a free spectral range (FSR) of approximately 100 GHz for the fundamental transverse-magnetic (TM_{00}) mode.

The microcomb has a measured free spectral range around 100.1 GHz and an estimated bandwidth exceeding 60 nm, which is shown in Figure 5(d). We achieved a remarkably low power threshold of approximately 6.5 mW for 100-GHz-FSR soliton microcombs, placing our results among the lowest power thresholds ever recorded for microcombs with electronically detectable FSRs. For context, the previous benchmark was set by a silicon nitride (SiN) microresonator with an intrinsic quality factor (Q) of 15 million, which generated a 99-GHz-FSR single soliton at an on-chip power of 6.2 mW. While our power threshold is comparable to this record, our device outperforms in terms of comb line power. The comb lines produced by our device exhibit power levels exceeding -20 dBm, which is substantially higher than those observed in the previous record-holding study.

4.2. Electro-Optic Modulation based Comb Generation

The configuration of electro-optic modulator based comb sources typically consists of a CW laser source whose output is directed through one or more electro-optic intensity or phase modulators. These modulators are driven by large-amplitude sinusoidal radio frequency (RF) signals, operating in a nonlinear regime. The key to comb generation in this setup lies in the large-signal modulation applied to the modulators. This modulation is characterized by RF drive voltages that are multiples of $V\pi$ (the voltage required to induce a π phase shift in the modulator). Such high-amplitude driving necessitates the use of high-power RF amplifiers to achieve the required signal strength. When the optical signal from the CW laser passes through the modulator driven in this nonlinear regime, it results in the introduction of higher-order modulation harmonics of the driving RF signal, which appear as sidebands around the central optical frequency defined by the input laser. These sidebands form the lines of the optical frequency comb. The spacing between the comb lines in this configuration is determined by the frequency of the driving RF signal. By carefully controlling the modulation parameters, it's possible to generate combs with wide spectral coverage and precise frequency spacing [7].

This generation can be explained and demonstrated considering the case of a single phase modulator driven by a large sinusoidal signal where the output signal can be expressed

$$E(t) = A(t) * \exp\,(i(2\pi f_c + \varphi_{CE} + \beta \sin\,(\phi t)) \qquad (3)$$

Where β and ϕ are the amplitude and angular frequency of the large phase modulating sinusoidal signal. Using the Jacobi-Anger expansion:

$$E(t) = \sum_{n=-\infty}^{\infty} A(t) J_n(\beta) e^{i(2\pi f_c + \varphi_{CE} + n\cdot\phi t)} \qquad (4)$$

Where J_n is the nth order first kind Bessel function. Multiple harmonics are observed symmetrically distributed around the central optical carrier frequency. The amplitude distribution of these comb tones follows a pattern described by Bessel functions, which is a direct consequence of the phase modulation process. As the modulation depth increases, energy from the carrier is transferred to the sidebands, creating higher-order harmonics. The relative amplitudes of these harmonics are determined by the modulation index and can be precisely predicted using Bessel functions of the first kind.

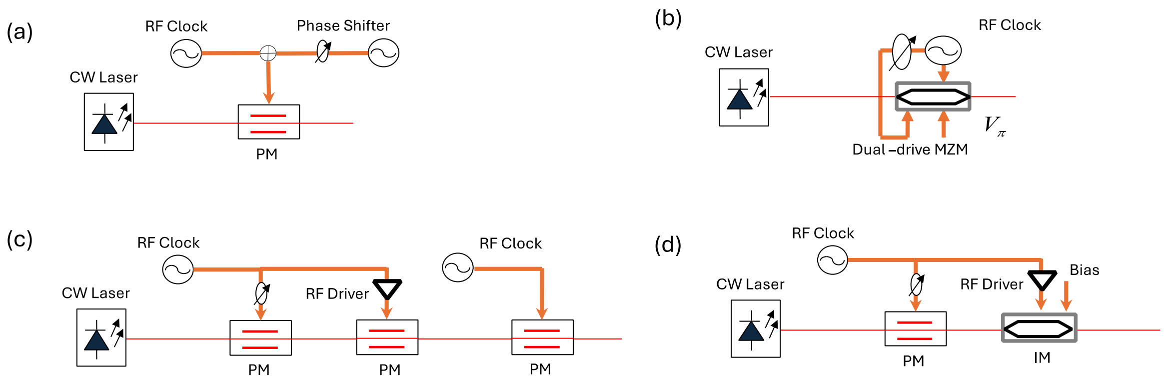


Figure 6 – Different Schematic Setups based on Electro-Optic Modulators for Frequency Comb Generation. PM: phase modulator; IM: intensity modulator

As illustrated in Figure 6, various electro-optic modulator configurations have been explored to achieve comb flattening and expansion, each offering unique advantages and challenges. These configurations range from relatively simple setups to more complex arrangements, each designed to optimize different aspects of comb generation. Figure 6(a) involves using a single phase modulator driven by combined RF signals with different amplitudes and frequencies. This method allows for some control over the comb spectrum but may have limitations in terms of flatness and bandwidth. The configuration of Figure 6(b) utilizes a dual-drive Mach-Zehnder modulator (MZM). This setup enables finer control over the comb generation process by allowing adjustment of the amplitudes, frequencies, and phases of the modulating signals. The dual-drive nature of the MZM provides additional degrees of freedom in shaping the comb spectrum.

Figure 6(c) involves cascading several phase modulators in series. This approach can significantly enhance the bandwidth of the generated comb by leveraging the cumulative effect of multiple modulation stages. However, it may introduce complexity in terms of synchronization and power requirements. A particularly balanced configuration, as illustrated in Figure 6(d), combines intensity modulators with phase modulators. This hybrid approach offers a good compromise between complexity, spectral flatness, and tuning flexibility. The intensity modulators can help shape the overall envelope of the comb, while the phase modulators contribute to expanding its bandwidth. This configuration allows for independent control of different comb characteristics, making it versatile for various applications.

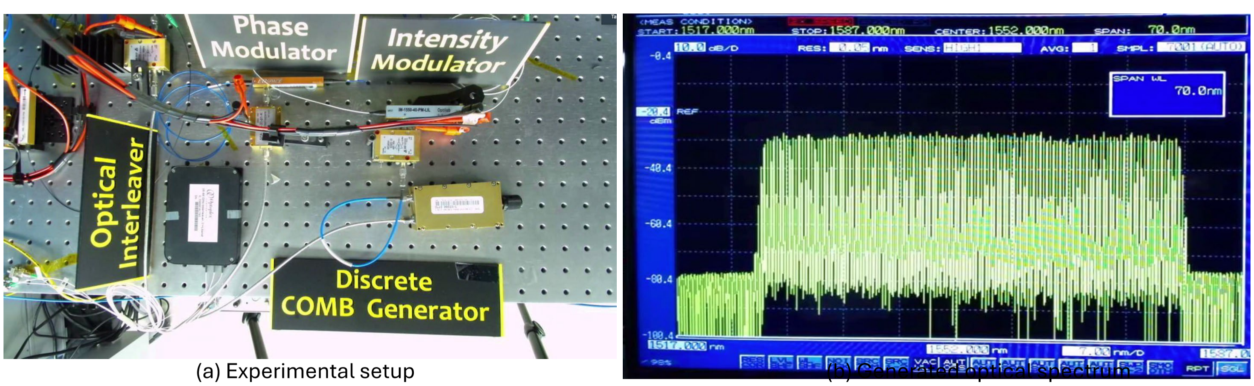


Figure 7 – Experimental Setup and Optical Spectrum with Cascaded IM and PM for Frequency Comb Generation.

Figure 7 presents a comprehensive view of the experimental setup photo, and the resulting optical spectrum achieved through a cascaded IM and PM scheme for optical frequency comb generation, representing the method of Figure 6 (d). The generated optical spectrum, illustrated in Figure 7(b), demonstrates the impressive capabilities of this comb generation technique. The system produces a total of 128 distinct optical carriers, spanning an impressive 50 nm wavelength range. This broad spectral coverage encompasses the entire C-band and extends into a portion of the L-band. In the frequency domain, this 50 nm wavelength span is equivalent to a bandwidth of 6.4 THz. The optical interleaver used in the setup combines the even and odd optical carriers to create a final spectrum with a uniform 50 GHz spacing between adjacent comb lines. This regular spacing is crucial for many applications, particularly in telecommunications where it aligns with standard channel grids used in DWDM optical systems.

4.3. Quantum Dot Laser for Comb Generation

Over the last ten years, semiconductor laser combs have undergone a revival, particularly in quantum cascade lasers (QCLs) and quantum-dot (QD) lasers. They are now considered a promising approach for comb generation. QD lasers, in particular, demonstrate several inherent optical properties due to their low-dimensional nanostructure. These properties include a low threshold current, broad emission spectrum, enhanced temperature stability, ultrafast carrier dynamics, and minimal relative intensity and phase noise.

The monolithic QD comb source that we developed is an InP-based p-n blocked buried heterostructure (BH) Fabry-Perot (FP) laser with uncoated facets. This laser structure consists of a 170 nm thick InGaAsP waveguide core with 10 nm $In_{0.816}Ga_{0.184}As_{0.392}P_{0.608}$ (1.15Q) barriers. It also includes five stacked layers of InAs QDs as the active gain region, surrounded by n- and p-type InP cladding layers. The InAs QD material was grown using chemical beam epitaxy (CBE) on precisely (001)-oriented n-type InP substrates, following a similar process to that described in the reference mentioned. The laser waveguide, which is 1692 µm long, was then fabricated using standard photolithography, dry-etching, wet-etching, and contact metallization techniques. After growing the laser core, a 2 µm wide waveguide mesa was created by etching through the 1.15Q waveguide core. This was followed by the selective area overgrowth (SAG) of a pnp blocking layer structure, which serves to confine carriers to the waveguide mesa. The final p-type InP cladding and contact layers were grown after removing the dielectric mask used for the SAG. To provide mechanical support, the QD laser chip was mounted on a commercially available AlN Chip-on-Carrier (CoC). Electrical connections were made using two Au electroplated contacts on the CoC. The cathode (bottom contact) of the QD laser chip was bonded with AuSn eutectic to one of the electrodes of the carrier, while the anode (top contact) was connected to the other electrode via wire bonding. Figure 8 (a) shows a visual representation of the laser chip on the CoC [8].

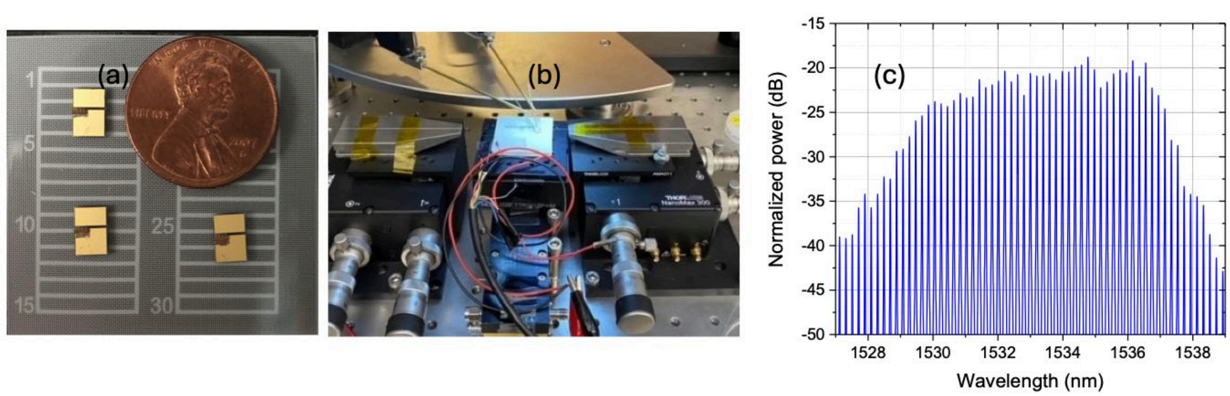


Figure 8 – (a) QD Laser Chip on AlN CoC. (b) Laser Test Setup. (c) Optical Spectrum (0.1nm resolution)

During testing, the laser was powered by a DC power supply through a pair of DC probes, while the temperature was controlled using a thermoelectric cooler (TEC). All tests were performed at a drive current of 360 mA and a temperature of 20 °C. The laser output was coupled into a polarization maintaining lensed fiber, as illustrated in Figure 8 (b) for a depiction of the laser test setup. The optical spectrum of the QD is shown in Figure 8 (c), with its center wavelength around 1534 nm and a frequency spacing of 25 GHz between adjacent comb tones.

5. Applications in Optical Communication Networks

The vision of the optical grid and optical power generation was presented earlier, now let's explore how optical frequency combs could revolutionize future optical networks. The optical frequency comb represents a groundbreaking advancement as an optical power generator in the optical grid vision. Unlike traditional systems that rely on multiple independent laser sources or laser banks, optical frequency comb technology enables a single comb to replace numerous expensive lasers. This innovation significantly reduces power consumption and system complexity, offering a more efficient and streamlined approach to optical networking.

It's important to note that every piece of optical equipment requires a light source. Frequency combs provide a low-cost solution for populating fiber strands with optical carriers, extending capabilities even beyond our conventional fiber transmission bands. This technology allows us to fill the available spectrum more efficiently, increasing data capacity and transmission rates. The cost-effectiveness of optical combs becomes even more apparent when we consider the scale of implementation. We can multiply the cost savings across the large number of high-quality carriers generated from a single transmitter. This multiplication effect amplifies the economic benefits, making optical frequency combs an attractive option for network operators and service providers looking to upgrade their infrastructure. The cost of generating high-quality optical carriers no longer will be a primary concern in implementing systems.

Furthermore, the precision and stability of combs open up new possibilities for advanced modulation schemes and network convergence. This could lead to increased fiber capacity, dedicated wavelength to the end user, and potentially a unified network platform, further enhancing the capabilities of optical networks. As we look to the future of optical communications, the integration of optical frequency combs stands out as a key enabling technology, promising to drive innovation and efficiency in high-speed, high-capacity optical systems.

5.1. Delivering 50Tb/s over a Single Fiber

We employ electro-optic modulation method for frequency comb generation, as illustrated in Figure 7. To combine and select different wavelength carriers, we utilize a wavelength selective switch (WSS). In our pursuit of achieving the promised 50Tb/s transmission rate, we have harnessed the power of polarization multiplexed coherent optical modulation and detection technologies.

The fundamental configuration for this setup is depicted in Figure 9. Each information carrier in our system is modulated with 34GBaud signals, utilizing two polarizations and a 64 Quadrature Amplitude Modulation (QAM) format. This configuration allows for 6 bits per symbol, resulting in a raw data rate of 408Gb/s per wavelength (calculated as 34 x 2 x 6). Our system incorporates a total of 128 optical carriers from comb with 50-GHz spacing, culminating in the total capacity of 52,224 Gb/s (or 52.224 Tb/s) over a single standard fiber.

CableLabs has developed a Graphical User Interface (GUI) to visualize and manage this complex system. The GUI displays 64-QAM constellations and incorporates the sophisticated algorithms that drive the demodulation process. These elements are also presented in Figure 9, providing a comprehensive view of both the physical setup and the software components that make this high-capacity transmission possible.

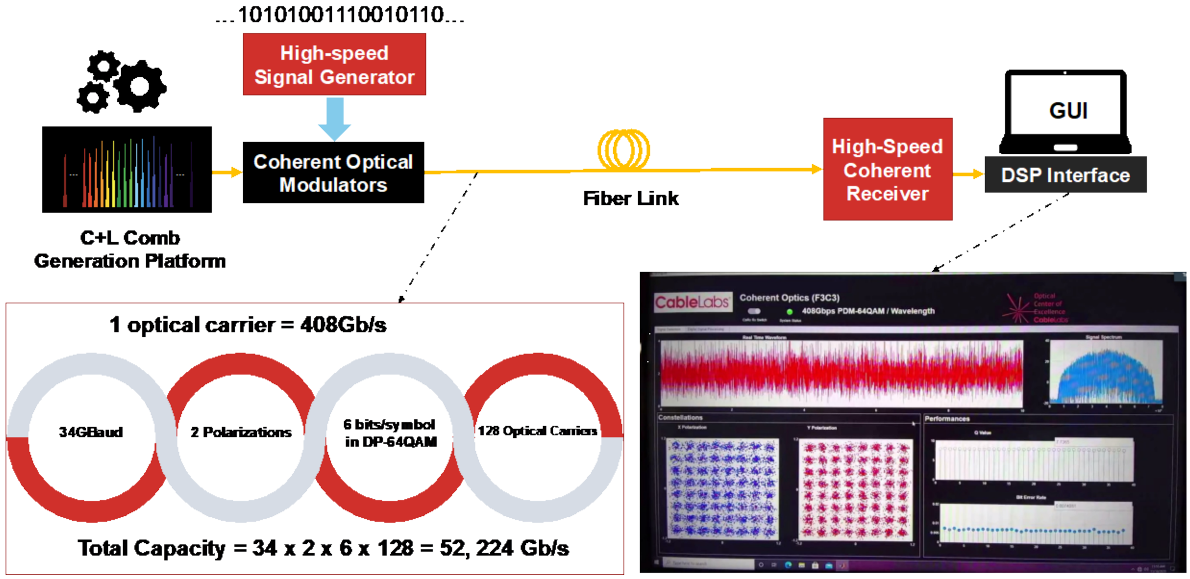


Figure 9 – Delivering 50Tb/s over a Single Fiber with the Use of the Electro-Optical Modulation based Optical Freqency Comb Laser Source

Figure 10 illustrates the optical spectrum for all channels, both before and after the application of coherent optical modulation. In practical implementations, modulator banks are essential for independent information modulation. This visual representation demonstrates the data capacity of approximately 50 terabits per second (Tb/s) achieved in this system. As pointed out earlier, each individual carrier within the spectrum is engineered to transport 408 gigabits per second (Gb/s) of data information. When we aggregate the data streams across all carriers in the entire spectrum, we realize a total transmission capacity of approximately 50 Tb/s over a single optical fiber. This remarkable feat underscores the potential for high-capacity optical communication systems in meeting the ever-growing demand for data transmission. The spectral efficiency of this configuration is noteworthy, achieving approximately 8 bits per second per Hertz (b/s/Hz). This high efficiency is crucial for maximizing data throughput within the available bandwidth. The spectrum utilized in this setup spans the entire C-band and extends into a portion of the L-band, thereby exploiting a wide range of available wavelengths for data transmission. This combination of high spectral efficiency and broad-spectrum utilization represents a significant leap forward in optical fiber communication technology, offering huge data transmission that can meet the ever-growing demand for bandwidth in our cable operators' optical access networks.

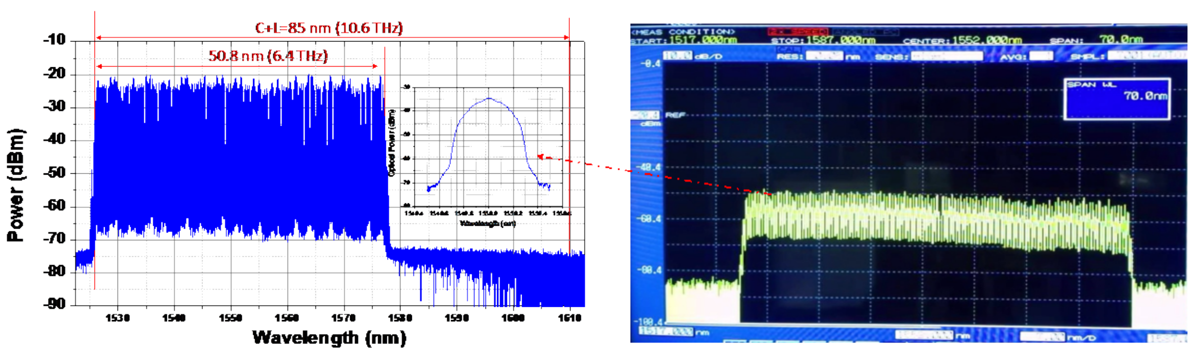


Figure 10 – Optical Spectrum after DP-64QAM Modulation

5.2. Delivering Fiber and Wireless Convergence

The convergence of fiber-optic and wireless technologies represents a pivotal development in current communication networks, driven by the ever-increasing demand for high-speed, reliable, and ubiquitous connectivity. As data consumption continues to grow exponentially, traditional network architectures are struggling to keep pace with user expectations and emerging applications. Fiber and wireless convergence offers a promising solution by combining the vast capacity and low latency of fiber-optic networks with the flexibility and mobility of wireless systems. This synergistic approach aims to leverage the strengths of both technologies, creating a seamless and robust communication infrastructure capable of supporting next-generation services such as 5G and beyond and advanced cloud computing applications. By integrating these complementary technologies, network operators can enhance coverage, increase bandwidth, and improve overall network performance while optimizing costs and resource utilization.

Optical frequency combs have emerged as a crucial building block that enables the convergence of fiber and wireless technologies, offering a powerful solution to bridge the gap between optical and radio frequency domains, as illustrated in Figure 11 for the conceptual system diagram.

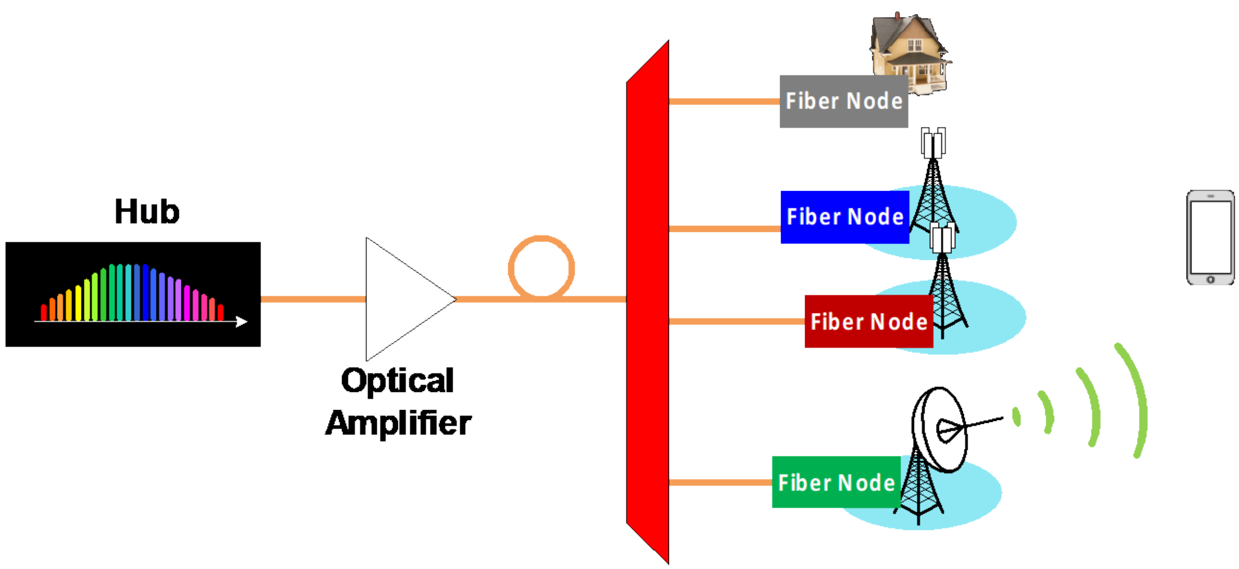


Figure 11 – System Diagram for the Convergence Platform

By generating precise and stable frequency references, optical frequency combs facilitate the seamless translation between optical and wireless signals, supporting the development of hybrid communication systems that can meet the growing demands for bandwidth and connectivity. The unique properties of optical frequency combs make them particularly well-suited for addressing the challenges of fiber and wireless convergence. They excel in generating ultra-stable microwave and millimeter-wave signals directly from optical frequencies, which is essential for high-frequency wireless communications in 5G and future 6G networks. Furthermore, their ability to simultaneously produce multiple carriers for both optical and wireless transmission enhances spectral efficiency and enables the creation of high-capacity, multi-band communication systems. The precise frequency spacing of the comb also allows for tight synchronization between optical and wireless networks, a critical factor in implementing advanced networking techniques such as coordinated multi-point (CoMP) transmission.

Figure 12 illustrates the converged fiber-wireless optical access network schematic diagram. In the hub, an optical frequency comb is generated using either electro-optical modulation, microresonators, or integrated QD lasers. An EWSS then separates different comb lines for various applications.

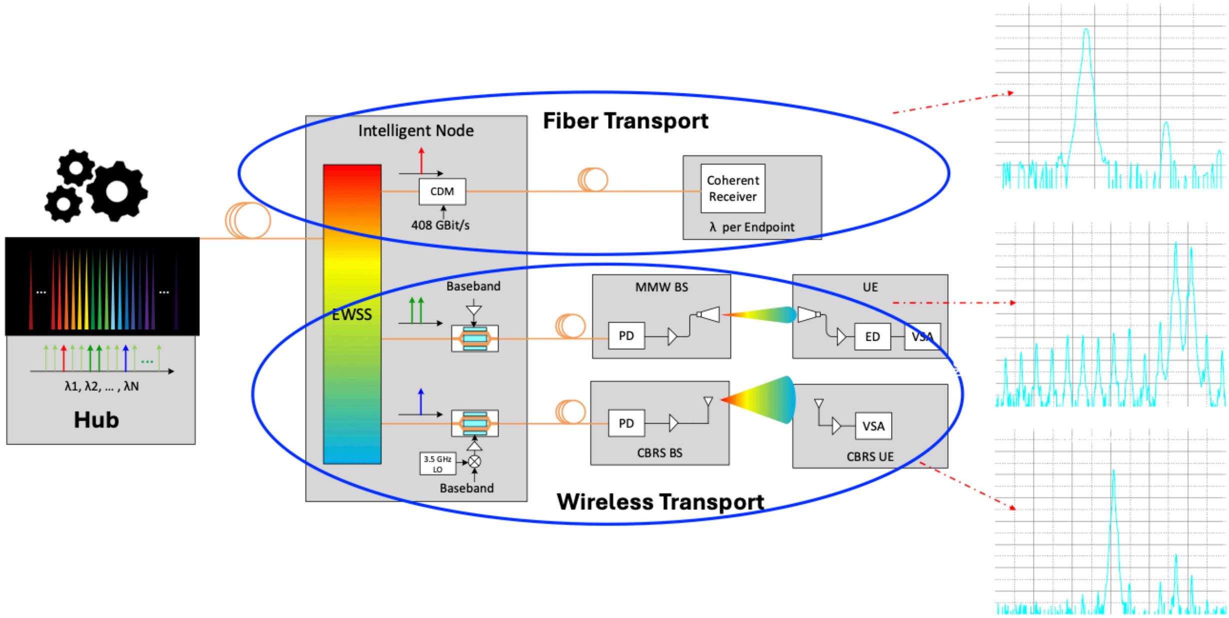


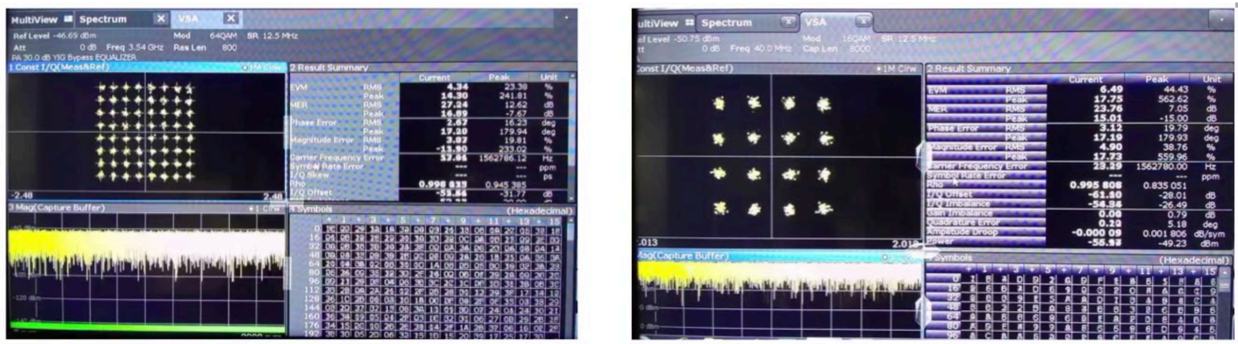
Figure 12 – System Setup for Fiber and Wireless Convergence Platform

The top blue ellipse depicts the use of one or more optical tones as carriers for point-to-point coherent signal generation and transmission. This process employs a coherent driver modulator (CDM) to assign a wavelength per endpoint.

The bottom blue ellipse focuses on wireless signal generation and distribution. For the mm-wave scenario, two continuous tones with 25-GHz spacing are selected, and the baseband signal is simultaneously modulated on both. After transmission through a 20 km single mode fiber (SMF) link, a photodiode (PD) at the millimeter wave (MMW) base station (BS) converts the optical signal to a 25 GHz MMW signal, which is then broadcast via a horn antenna. On the user equipment (UE) side, another horn antenna about 2 m (for illustration purpose) away receives the MMW signal, which is then processed by an envelope detector (ED) connected to a video signal analyzer (VSA).

In the Citizens Broadband Radio Service (CBRS) transport scenario, a single tone is modulated by another MZM with electrical up-conversion at 3.5 GHz. A 20 MHz 64-QAM based CBRS signal is transmitted over the 3.5 GHz carrier. Following the 20 km SMF link, a PD at the CBRS BS converts the optical signal to a CBRS signal, which is then broadcast using an omnidirectional antenna. On the UE side, approximately 2 m (for illustration purpose) from the BS, a mount style antenna detects the CBRS signal and feeds it to another VSA for analysis. All the corresponding spectral diagrams are also inserted in Figure 12.

Figure 13 displays the results obtained on the VSA for wireless signals transmitted through both optical fiber and air, demonstrating the system's capability in handling different transmission media. It shows a 20 MHz 64-QAM based wireless signal transmitted over a 3.5 GHz carrier and a 20 MHz 16-QAM based wireless signal transmitted over a 25 GHz mmWave carrier. These signals were generated using an electro-optic modulation based frequency comb generation method. For more detailed transmission performance data, refer to the paper that utilizes a QD laser for frequency comb generation [8].



(a) 20MHz 64QAM based wireless signal over 3.5GHz carrier

(b) 20MHz 16 QAM based wireless signal over 25GHz carrier

Figure 13 – Constellations after Fiber and Air Transmissions

6. Challenges and Discussions

Despite the superior technical features demonstrated by optical frequency combs and their successful applications in fields for improving the accuracy of atomic clocks and enhancing measurement techniques in metrology, However, the telecommunications sector, which could potentially benefit greatly from this technology, has been slow to adopt and integrate optical frequency combs into its infrastructure. The reasons for this are multifaceted, several key improvements are necessary for widespread adoption, as shown in Figure 14.

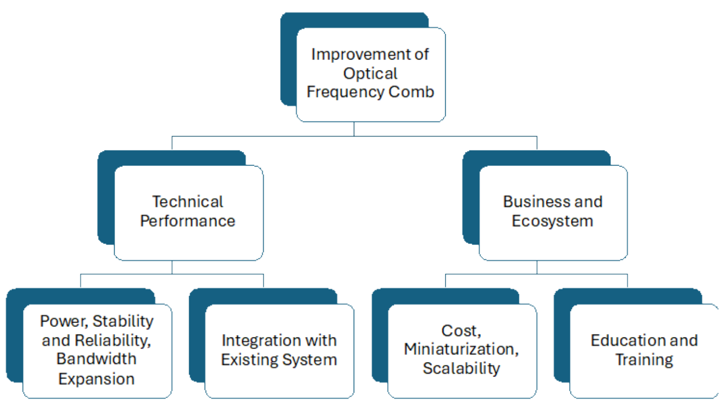


Figure 14 – Key Necessary Improvements for Wide Adoption of Optical Frequency Combs

At the forefront of these challenges is the need for substantial improvements in technical performance. Currently, the power per comb line ranges from -10 to 2 dBm, which is insufficient for many communication applications. Researchers are working to increase this output to 8-12 dBm, a level necessary for maintaining signal integrity over long distances and ensuring high data transmission rates. However, this effort must balance against another system challenge: managing the overall power per wavelength (lambda) to prevent fiber nonlinearities. Excessive power can induce nonlinear effects in the fiber, requiring more complex and power-hungry correction mechanisms in network nodes. The 'sweet spot' for power depends on various factors including fiber type, transmission distance, and modulation scheme, but typically falls in the range of 0 to 5 dBm per channel for most of optical systems. This improvement process involves carefully balancing the use of optical amplifiers while maintaining a high optical signal-to-noise ratio to preserve signal quality and prevent data loss. Additionally, efforts are underway to minimize power variations across comb lines and enhance overall power efficiency. These advancements are particularly important for practical applications in data centers and network nodes, where energy consumption and heat generation are significant concerns. By addressing these technical challenges, researchers aim to make optical frequency combs a viable and efficient alternative to traditional communication lasers, potentially revolutionizing telecommunications and data transmission technologies.

Long-term stability and reliability across diverse environmental conditions, from controlled data centers to outdoor installations, require robust designs that can withstand various stresses. Simultaneously, expanding the bandwidth of high-quality comb lines is crucial for increasing data transmission capacities to meet growing demands from emerging technologies. Seamless integration with existing telecommunication systems, particularly wavelength-division multiplexing and other critical technologies, presents both challenges and opportunities. The goal is to enhance network performance by creating a symbiotic relationship between frequency combs and current technologies without necessitating a complete system overhaul. Addressing these challenges could lead to significant cost savings and performance improvements for telecommunication providers, enabling more efficient data transmission over existing infrastructure. Advancements in signal processing techniques are also crucial for maximizing the potential of frequency comb-based systems. This involves developing more efficient algorithms and specialized hardware capable of handling the unique characteristics of frequency comb signals [9]. Improved signal processing can lead to better noise reduction, more accurate data recovery, and increased transmission rates, all of which contribute to enhanced overall system performance. Integrating frequency combs with injection locking also enhances spectral purity, improves phase noise characteristics, and enables precise frequency control. It allows for the generation of high-quality, stable optical carriers, which are crucial for advanced modulation formats and coherent detection schemes [10].

The adoption of frequency comb technology faces several business and ecosystem challenges. High costs are a primary hurdle, necessitating efforts to reduce production expenses and develop more affordable components through improved manufacturing processes and materials science. Miniaturization is crucial for integration into existing telecom infrastructure, with researchers leveraging photonic integrated circuit technology to create compact, efficient comb generators. Demonstrating scalability for large-scale network deployments is essential to build industry confidence, addressing both technical feasibility and practical concerns like maintenance and reliability. Education and training initiatives are vital to increase awareness among telecom professionals and decision-makers about the benefits and applications of frequency combs.

Extending the applications of optical frequency combs in data center networks is crucial for accelerating their widespread adoption. Currently, much of the development and innovation in optical devices and systems is driven by data center operators, who are constantly seeking ways to enhance their infrastructure's capacity and speed. By focusing on applications specific to data centers, researchers and engineers can align their efforts with the needs of these major industry players [11]. Optical frequency combs offer significant advantages for data center networks, particularly in handling massive data traffic through parallel communication links. Their ability to generate multiple wavelengths simultaneously enables data transmission across multiple channels, increasing overall bandwidth without additional physical infrastructure. This is especially valuable in space-constrained environments. The integration of frequency combs with copackaged optics (CPO) could lead to more compact, energy-efficient, and high-performance optical interconnects within data center switches and servers. For intra-data center connectivity, frequency combs could revolutionize data transmission between racks and servers, reducing latency and increasing throughput for short-range connections. This could benefit applications requiring real-time processing or dealing with large datasets, such as AI and machine learning workloads. Additionally, the precise nature of frequency combs could improve synchronization across the entire data center network, enhancing time-sensitive applications and maintaining data consistency in distributed systems.

While the potential benefits of integrating optical frequency combs into data center networks are substantial, it's important to note that there are challenges that were pointed out earlier in this section. However, as data traffic continues to grow exponentially and energy efficiency becomes increasingly critical, the advantages offered by optical frequency comb technology may well outweigh these initial hurdles.

7. Conclusion

Optical frequency combs represent a paradigm shift in optical communication networks, offering a unique blend of efficiency, cost-effectiveness, and performance enhancement. As explored in this work, these innovative light sources provide numerous advantages, including densely packed optical carriers, reduced power consumption, and improved system performance through integration and advanced signal processing. We introduced multiple optical frequency comb generation approaches. Our key findings highlight the potential for optical frequency combs to replace multiple discrete lasers in DWDM transmitters and receivers, which could simplify system design and reduce costs. We demonstrated the capability to transmit up to 50 Terabits per second over a single access network fiber, showcasing the technology's capacity to dramatically increase network throughput. Additionally, we found that these combs can generate low-noise millimeter-wave signals, facilitating the convergence of wired and wireless networks. A converged optical-wireless DWDM access network architecture is then presented for future access network architecture, illustrating the versatility of frequency comb technology.

While challenges remain in integrating frequency combs into our existing cable communication networks, the potential benefits are substantial. As the industry moves forward, it is crucial to continue research, development, and implementation of optical frequency comb technology. By doing so, we can unlock new possibilities in network capacity, efficiency, and convergence, ultimately leading to more robust and advanced cable fiber network infrastructure. The cable industry is urged to embrace this transformative technology, invest in its development, and work towards overcoming integration challenges. By leveraging optical frequency combs, we can maintain a competitive advantage and pave the way for the next generation of optical communication networks.

Abbreviations

AP	access point
bps	bits per second
b/s/Hz	bits per second per Hertz
BS	base station
CBRS	citizens broadband radio service
CoC	chip-on-carrier
CW	continuous wave
DFB	distributed feedback
DWDM	dense wavelength division multiplexing
ECL	external cavity laser
ED	envelope detector
EWSS	edge wavelength switching system
FEC	forward error correction
FSR	free spectral range
FWM	four wave mixing
Gb/s	gigabits per second
GUI	graphical user interface
HD	high definition
Hz	hertz
IM	intensity modulator
K	kelvin
MLL	mode-locked laser
MMW	millimeter wave
MZM	Mach-Zehnder modulator
PIC	photonic integrated circuits
PM	phase modulator
Q	quality factor
QAM	quadrature amplitude modulation
QCL	quantum cascade laser
QD	Quantum dot
RF	radio frequency
RIN	relative intensity noise
SiC	silicon carbide
SiN	silicon nitride
SMF	single mode fiber
SWaP	size, weight, and power consumption
TEC	thermoelectric cooler
Tb/s	terabits per second
UE	user equipment
WSS	wavelength selective switch

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