Next-generation mobile communication leveraging cutting-edge photonic technologies (Photonic 6G)

All-photonic THz generation based on soliton microcomb.

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Since 2020, commercial services for the 5th-generation mobile communication system (5G, operating at frequencies up to 28 GHz) have been launched in Japan, promising diverse 5G services characterised by ultra-low latency, ultra-high speeds and simultaneous connections. Simultaneously, research and development efforts have intensified for the next-generation mobile communication system (6G), scheduled to debut in 2030, operating at frequencies exceeding 300 GHz (Dang *et al.*, 2020). 6G aims to build upon the advancements of 5G, with an emphasis on improved reliability and power efficiency, in addition to further enhancing its features.

However, unlike the progression of previous mobile communication systems (2G/3G/4G/5G), which relied heavily on electronic technology innovations and higher frequencies, 6G may face fundamental challenges due to the potential limitations of electronic technology, particularly regarding the upper limits of frequency, as it ventures into the terahertz (THz) frequency range (above 300 GHz). Issues such as low output power, increased phase noise, and increased signal transmission losses may become prominent (Figure 1, upper part).

To overcome these challenges, a paradigm shift, surpassing the frequency limits of electronics, is imperative. Moreover, while 6G offers the potential to bridge the transmission speed gap between optical and wireless communication, a technical gap exists due to differences in optical and electrical technologies, resulting in time delays during the conversion of optical and electrical signals (Figure 1, lower part). A 'seamless connection between optical and wireless communication' is required to achieve ultra-low latency in 6G while seamlessly integrating optical and wireless communication. Simultaneously addressing these two technical challenges necessitates exploring mobile communication methods with minimal electronic intervention. In this context, photonic methods (photonics) are considered promising (Nagatsuma, Ducournau and Renaud, 2016).

Optical frequency comb (OFC) (Udem, Holzwarth and Hänsch, 2002) has significantly advanced spectroscopy as an 'optical frequency ruler' by offering an ultra-discrete multispectral structure where numerous optical frequency modes align equidistantly in a comb-like pattern (Figure 2). In recent years, utilising optical combs as 'frequency gear (or converter) from optical signal to electric signal' has enabled the generation of ultra-low phase noise, electric frequency signals surpassing the quality of electronic methods by orders of magnitude. Furthermore, extremely low phase noise optical-to-THz conversion technologies (e.g. uni-travelling carrier photodiode or UTC-PD) (Ishibashi and Ito, 2020) have been established, paving the way for a technological shift from electrical to optical methods in mobile communication carrier generation. However, current OFC sources (e.g. fibre-based optical combs or electro-optic modulator-based optical combs) are medium-sized, complex and expensive. Additionally, their fundamental frequency (optical frequency mode spacing, f_{rep}) ranges from 100 MHz to 40 GHz, which is low compared to 6G carrier frequencies, leading to phase noise amplification during optical frequency multiplication. Addressing these issues could facilitate the transition from electrical to optical methods in 6G carrier generation, making 'paradigm shifts beyond the frequency limits of electronics' and 'seamless connection between optical and wireless communication' realistically attainable.

We aim to realise an 'all-photonic THz communication technology (Photonic 6G)' that minimises electronic intervention by merging and advancing state-of-the-art photonic technologies. By employing soliton microcombs (Liu *et al.*, 2020; Shen *et al.*, 2020) with

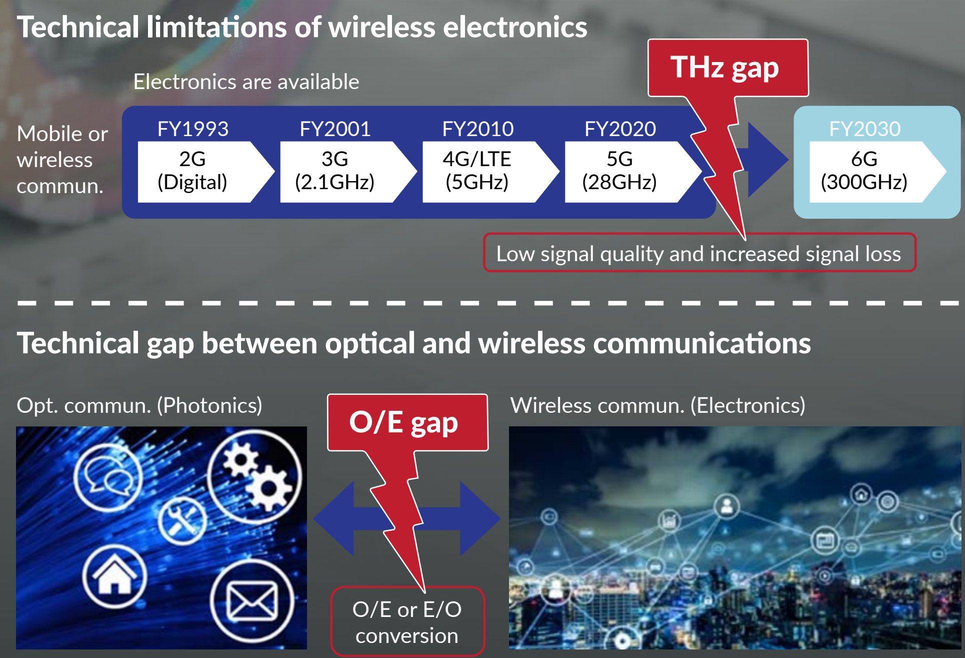

Figure 1: Two technical challenges faced by 6G.

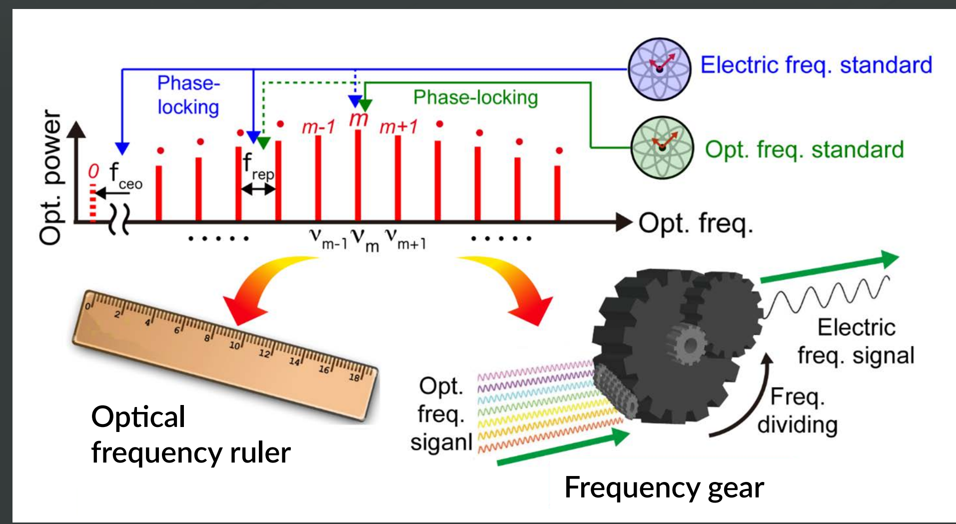

Figure 2: Optical frequency comb (OFC).

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low phase noise, which have optical frequency mode spacing (f_{rep}) equal to 6G carrier frequencies, we generate low-phase-noise THz waves (all-photonic THz generation, Figure 3, top left) (Zhang *et al.*, 2019; Tetsumoto *et al.*, 2021; Kuse *et al.*, 2022). Simultaneously, we use an electrical-optical polymer modulator to convert modulated THz waves with superimposed transmission information into optical carrier signals extracted from OFC, subsequently detecting the baseband signal as an optical beat signal (all-photonic THz detection, Figure 3, top right) (Matsumura *et al.*, 2023). By leveraging the advantages of both steps, we perform advanced modulation and demodulation entirely within the optical domain, enabling multi-level modulation and multiplexing for 6G (all-photonic THz modulation/demodulation, Figure 3, bottom left) (Tokizane *et al.*, 2023a,b; Tokushima University 2023a,b). Ultimately, by integrating these three all-optical THz communication element technologies, we aspire to achieve 'all-photonic THz communication (Photonic 6G)' (Figure 3, bottom right).

In this article, we introduce the outcomes of our research related to all-photonic THz generation (Kuse *et al.*, 2022).

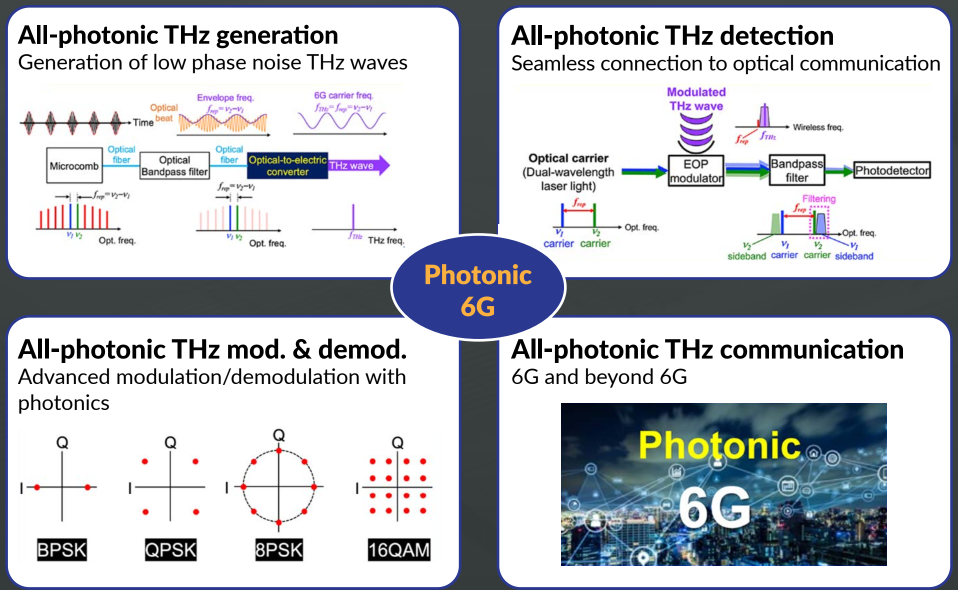


Figure 3: 6G boosted by advanced photonics (Photonic 6G).

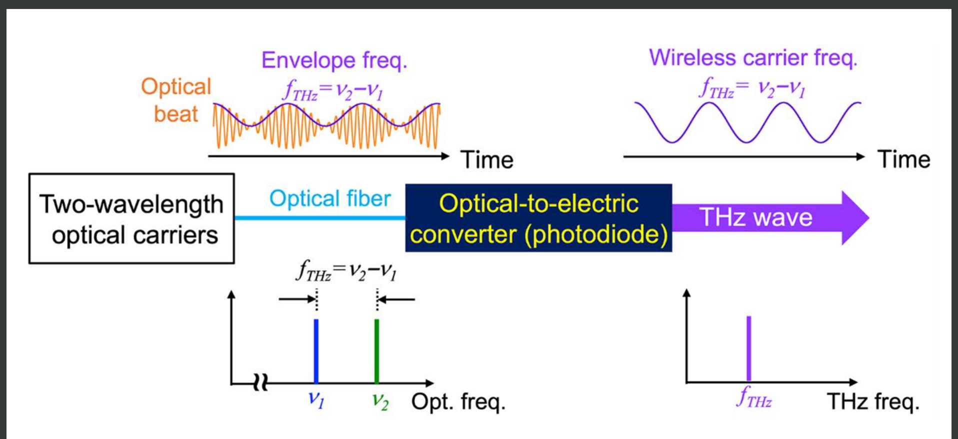


Figure 4: THz generation based on photomixing of two-wavelength optical carriers with photodiode.

Photonic THz generation based on photomixing of soliton microcomb with UTC-PD

In photonic methods used to generate THz waves, two optical carriers separated by THz frequencies are directed onto a fast photodetector (UTC-PD), as shown in Figure 4. Subsequently, a THz wave is generated through an optoelectric conversion process. The phase noise of these generated THz waves is intrinsically tied to the relative phase noise between the two optical carriers.

As elucidated in Table 1, prevailing photonic methods typically employ two single-frequency continuous-wave (CW) lasers or two optical modes extracted from electro-optic (EO) combs. The deployment of two CW lasers is advantageous due to its commendable frequency scalability and integration capability; however, it suffers from poor phase noise. On the contrary, methods that incorporate EO combs manifest a significant enhancement in phase noise. However, this comes at the expense of frequency scalability and integration capability, primarily due to the obligatory incorporation of higher-order optical side modes. Venturing beyond these conventional methods, our research is centred on pioneering a novel approach that capitalises on Kerr microresonator optical frequency combs, termed microcombs (Liu *et al.*, 2020; Shen *et al.*, 2020).

Microcombs are generated by introducing a CW laser into a microresonator constructed from ultra-low loss optical waveguides, as shown in Figure 5. When the intensity of the CW laser exceeds a certain threshold, a nonlinear optical effect is initiated. This results in the primary optical carrier dividing into multiple carriers, known as comb modes, leading to the formation of OFC. Given that both CW lasers and microresonators can be fabricated using a CMOS-compatible process, microcombs can be produced on a chip-scale and are mass-producible. The free-spectral range (FSR) of microresonators ranges from 10 GHz to 1 THz, which corresponds to the spacing of the comb modes (= f_{rep}). These characteristics make microcombs particularly apt for THz wave generation, ensuring both frequency scalability and integration capabilities.

Among the diverse operational states of microcombs, the single soliton comb is particularly noteworthy for its minimal noise; a characteristic attributable to mode-locking, where balances between gain-loss and dispersion-nonlinearity are achieved. The comb modes inherent to soliton combs are highly correlated, resulting in a phase noise that is demonstrably superior to that observed in two independent CW lasers. Yet, the phase noise exhibited by soliton combs doesn't quite match the benchmarks set by frequency-multiplied electronics or EO combs. Addressing this gap, our research led to the conceptualisation and development of a novel system (Kuse *et al.*, 2022). This system is capable of generating a THz wave characterised by a groundbreaking phase noise value of -100 dBc/Hz at a 10 kHz frequency offset for a 560–GHz carrier.

The system we have developed is segmented into three primary parts (Figure 6(a)). The first part is a soliton comb. The second part involves detecting the phase noise of f_{rep} of the soliton comb and stabilising this noise using a long fibre. The third part focuses on generating a THz wave from the low-noise soliton comb. To detect the phase noise of f_{rep} of the soliton comb, we developed a method termed the two-wavelength delayed-self heterodyne interferometer (TWDI) (Figure 6(b)). TWDI consists of an unbalanced Mach-Zehnder interferometer (u-MZI) equipped with a long fibre for self-referencing and an acousto-optic modulator (AOM) for heterodyning in one arm, followed by two optical bandpass filters (OBPFs) at the two outputs from the u-MZI. Each OBPF extracts two comb modes at different wavelengths, and these modes are directed to two photodetectors. Due to the long fibre, the signals from the photodetectors reflect the phase noise of the detected comb modes. Since our target detection is the phase noise of f_{rep}, not the independent comb modes, the signals from the photodetectors are combined using a double-balanced mixer, producing the phase noise of f_{rep} while

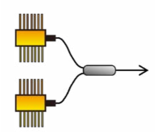
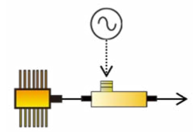
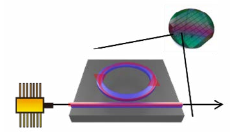
	Two CW lasers	EO comb	Microcomb
Configuration			
Frequency scalability	> 1 THz	< 300 GHz	< 1 THz
Integration	Good	Not good	Good
Phase noise (dBc/Hz at 10 KHz offset)	-50	-80	Under study

Table 1: Comparison of photonic methods used to generate THz waves.

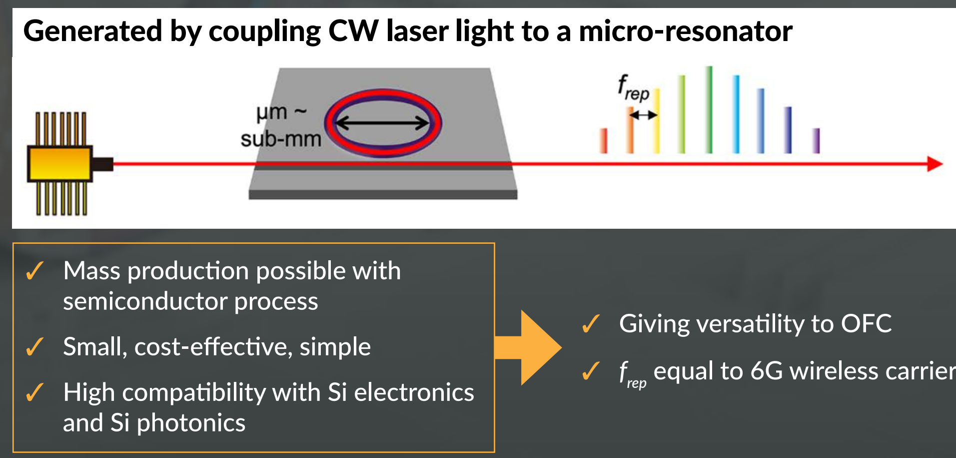


Figure 5: Microcavity OFC (microcomb).

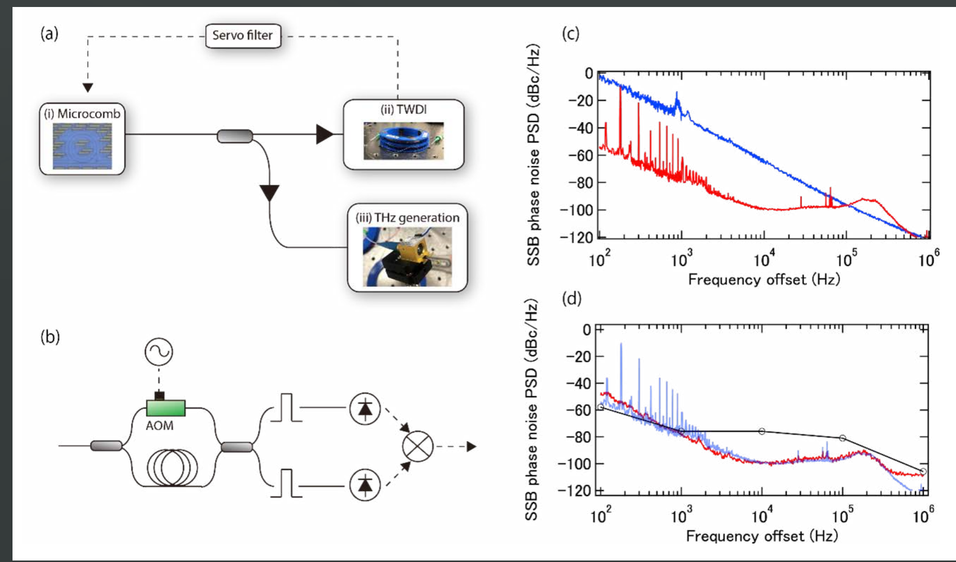


Figure 6: (a) Conceptual schematic of the generation of a low-phase-noise THz wave. (b) Schematic of the TWDI. (c) Phase noise of f_{rep} with (red) and without (blue) the feedback loop. (d) Phase noise of THz waves generated from the stabilised soliton comb(red). The phase noise of frequency-multiplied RF synthesiser (E8257D from Keysight) is also shown (black). The light blue curve is the phase noise of the f_{rep} of the stabilised soliton comb.

cancelling the phase noise of the CW laser. The detected phase noise of f_{rep} serves as an error signal for a feedback loop. To close this loop, the phase noise of f_{rep} is processed by an analogue PID loop filter and fed back to the pump CW laser. As a demonstration, the f_{rep} of the soliton comb was set at approximately 560 GHz, which can be easily adjusted by altering the size of the microresonators. Figure 6(c) displays the phase noise of the f_{rep} both with and without the feedback loop. Stabilisation reduces the phase noise by over 40 dB across a wide frequency offset, reaching -100 dBc/Hz at a 10-kHz frequency offset. The stabilised soliton comb is used to generate a THz wave, faithfully transferring the phase noise to the THz wave, as depicted in Figure 6(d). The phase noise of a high-end electronic synthesiser is also plotted. The phase noise of the THz wave produced by our system surpasses that of the synthesiser. This result also indicates that our phase noise is superior to a THz wave generated from an EO comb, as the latter equals the phase noise of the electronic synthesiser.

In conclusion, our system leverages the advantages of photonics in terms of both frequency scalability and phase noise, laying the foundation for our P6G technology that goes beyond current electronic capabilities.

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PROJECT NAME
PHOTONIC 6G

PROJECT SUMMARY

Our aim is to develop 'Photonic 6G', an all-photonic THz communication technology, by integrating advanced photonic methods. This includes generating low-phase-noise THz waves with microcombs and converting modulated THz waves into optical carrier signals. By leveraging these advancements, we aim to enable advanced modulation and multiplexing in the optical domain, ultimately achieving the integration for photonic 6G.

PROJECT PARTNERS
National Institute of Information and Communications Technology, Gifu University and Nagoya Institute of Technology

PROJECT LEAD PROFILE
Professor Takeshi Yasui, based at Tokushima University, Japan, boasts a distinguished career in THz photonics. His work has led to THz comb, spectroscopy and imaging breakthroughs. He is in charge of a chief research officer in the Institute of Post-LED Photonics. Prof. Yasui's research interests encompass THz photonics, optical comb and nonlinear microscopy, contributing significantly to advancements in these fields.

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