Design of a Photonic Integrated Circuit for 6G Terahertz Signal Generation at J-band (220-325 GHz) for ARoF systems

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Addressing the challenge of supporting the rapid growth of wireless devices in our daily life is crucial challenge for 6G wireless networks. A promising solution is exploiting of millimeter-wave/sub-THz frequency bands that can provide significant larger bandwidth compared to microwave bands. This work presents the concept of a tunable terahertz source generator implemented as a photonic integrated circuit based on InP platform for Analog Radio over Fiber (ARoF) systems. Self-injection locking technique of two Distributed Feedback (DFB) lasers with a microring resonator is explored, with the potential to improve phase noise performance. Additionally, optical single-sideband generation is achieved through dual-parallel Mach-Zehnder modulators, enabling carrier frequencies anywhere within the J-band (220-325 GHz). This circuit also supports the transmission of data with various modulation formats, including NRZ, QPSK, and more, offering flexibility for different communication standards.

Introduction

The rapid growth of connected smart devices and the increasing demand for faster wireless connections has motivated the exploration of new frequency bands beyond microwave and mm-wave bands. Therefore, terahertz bands are expected to be exploited by future 6G mobile networks to achieve challenging key performance indicators such as data rate approaching 1 Tbps and end-to-end latency below 1 ms to enable computational heavy applications such as AI, Internet of Everything and digital twins, or ultra-low latency applications such as autonomous driving and smart factories [1].

Data transmission in the sub-THz frequency range (0.1 – 10 THz) is considered one of the potential solutions to these challenges of 6G networks, because of their broad available bandwidth. More specifically, J-band (220–325 GHz) is of particular interest due to its atmospheric transparency, that makes it suitable for broadband wireless communications. A significant effort has been dedicated to the development of practical transceivers operating in this frequency band. A popular approach consists in utilizing semiconductor electronic transmitters based on Silicon-Germanium [2], [3] or InP HEMT [4]. Another popular approach leverages on electro-optic technologies that exploit the broadband nature of photonics components [5]. Moreover, the hybrid photonic approach enables Analog Radio over Fiber (ARoF) architecture for mobile fronthaul networks [6]. ARoF offers key advantages such as simplification of the base station, the direct tuning of mm-wave carriers by adjusting the optical carrier and centralization of the baseband processing as shown in Figure 1 [7]. However, besides the challenge of developing photodetector with broad bandwidth, the development of frequency stable and low phase

noise optical source is a critical part of ARoF systems for enabling phase detection, thus enabling quadrature modulation formats [8].

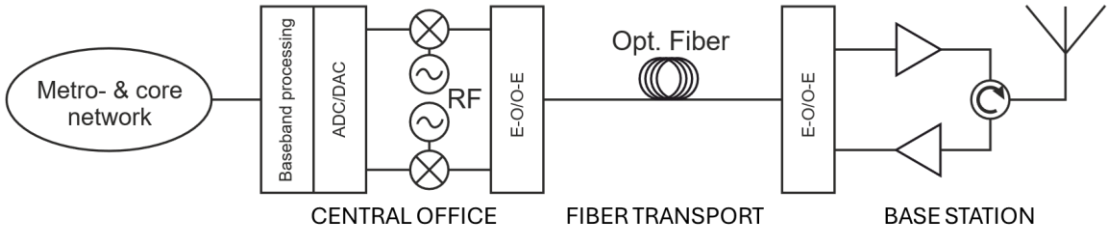

Figure 1: ARoF schematic for fronthaul fiber connections.

In this paper we report our concept of photonic transmitter based on Photonic Integrated Circuit (PIC) technologies for THz ARoF fronthaul links. The proposed PIC transmitter has a potential broad tuning across various frequency bands, low phase noise by phase locking the laser sources and to support single sideband (SSB) and coherent modulation schemes.

System Design

The proposed scheme leverages two independent DFB lasers close to 1550 nm that feed resonant Rayleigh backscattered light from a microring resonator to implement the self-injection locking technique [9], [10]. We expect this configuration to enable a stable frequency difference and a well-defined phase between the lasers. Another microring resonator will be used as optical demultiplexer. In one path, the optical wave is modulated using I/Q modulator for data transmission. In the other path, a Dual-Parallel Mach-Zehnder Modulator (Dual-Parallel MZM) can shift the carrier frequency of the optical light [11]. Depending on phase shift between the two arms, the frequency shift can either be positive or negative to the original frequency. Moreover, incorporating semiconductor optical amplifiers (SOAs) in both arms would further enhance the system's performance by compensating for potential signal losses. After modulation and amplification, two waves are combined using 3 dB directional coupler and transferred to the fiber output.

We are going to design a Photonic Integrated Circuit (PIC) on the HHI InP platform, which enables the integration of both passive and active components, including DFB lasers and SOAs. This design is also should contain a ring resonator with Free Spectrum Range(FSR) around 30 GHz in order to reach coarse frequency differences using matching the laser and resonant frequency of the microring resonator. Fine tuning will be reached using Dual-Parallel MZM.

As an alternative, we consider an external microring resonator for self-injection locking based on a Silicon Nitride platform, which can be connected to the InP photonic integrated circuit (PIC) using either optical fiber or edge coupling approaches [12]. It should be noted that more frequent FSR can enable operating not only in J-band, but also in W-, D- and other frequency bands.

Phase shift in the arms of Dual-Parallel MZM must be $\frac{\pi}{4} and \frac{3\pi}{4}$ to achieve single-sideband modulation, while the phase shift of the two RF inputs of Dual-Parallel MZM must be 90°. To effectively suppress the original carrier tone of the LO laser, the Extinction Ratio (ER) of MZM must be more than 20 dB. On the other harm the Dual-Parallel MZM is configured as an I/Q modulator so that it can support data transmission with phase modulation formats such as M-PSK and M-QAM. The general schematic of the PIC is shown in *Figure 2*.

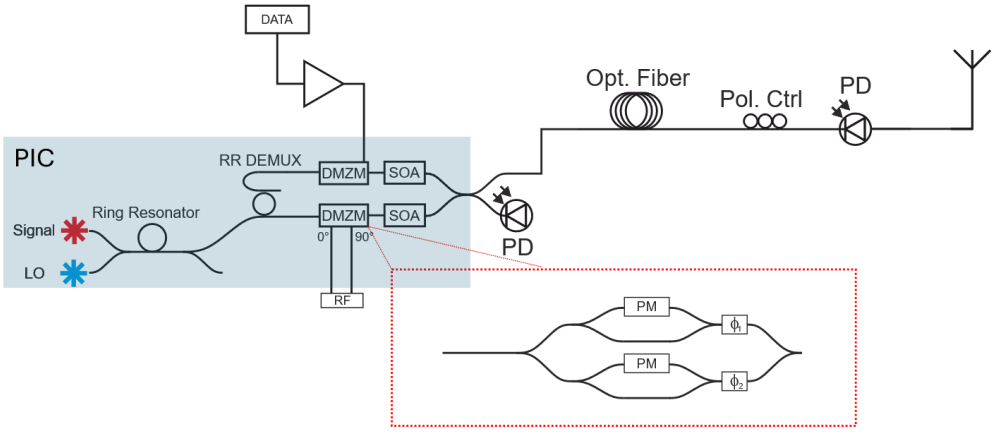

Figure 2: Principal scheme of ARoF transmitter; Dashed rectangle highlights the photonic section of the transmitter; DMZM represents Dual-parallel Mach-Zehnder Modulators with additional DC phase shifters, PM – Phase Modulator, SOA – Semiconductor Optical Amplifier

Simulations & Results

We simulated in ANSYS Lumerical Interconnect part of proposed PIC transmitter using single-frequency laser sources, Dual-Parallel MZM, single MZM with NRZ datarate, 3 dB directional coupler and ideal PIN photodiode. To simulate the SSB carrier frequency shifting of LO laser we used sinusoidal RF signals at 10 GHz for Dual-Parallel MZM. All MZMs are set to 30 dB ER. On the receiver side we used an electrical amplifier with 40 dB gain, band-pass filter for waveguides emulation and electrical mixer with sinusoidal local oscillator to simulate envelope detection. After the mixer another electrical amplifier was used as baseband amplifier. To simulate bandwidth of the receiver, it was used Butterworth low-pass filter with cut-off frequency of 18.75 GHz. Simulation scheme is presented in *Figure 3*. Simulation results are shown in *Figure 4*.

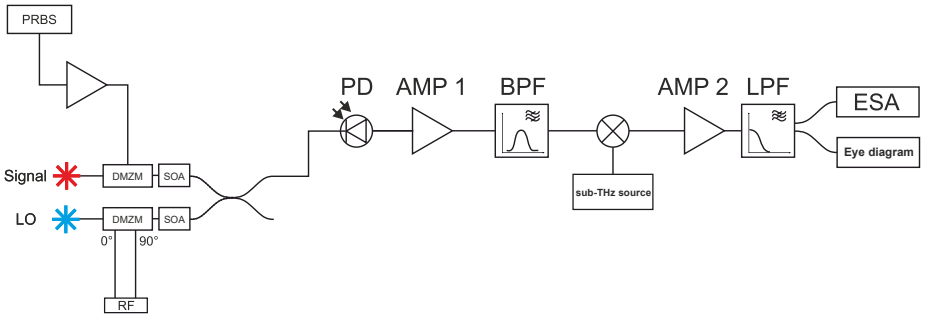

Figure 3: Simulated schematic of the ARoF link with SSB modulation based on proposed PIC.

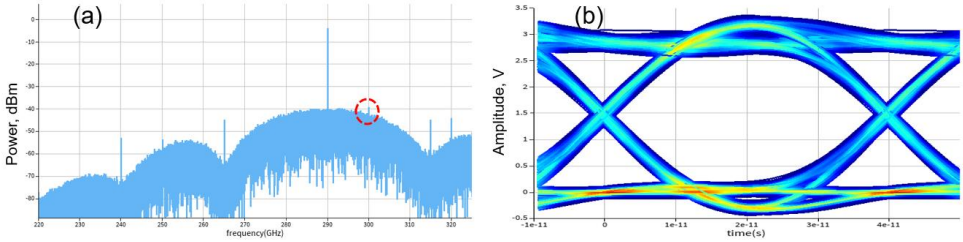

Figure 4: Simulation results; (a) Shifted spectrum of 25 Gbps NRZ signal. Dashed circle demonstrates non-ideal suppression of two-laser beatnote
(b) Eye diagram of 25 Gbps NRZ signal

Conclusion

We presented the concept of a compact, tunable and phase locked two-frequency optical source for ARoF applications with the potential of use across various frequency bands in wireless mm-wave communications. This scheme also supports the use of different modulation formats, offering greater flexibility in signal transmission. Further investigation is required to evaluate the self-injection locking technique in this implementation, which enhances the phase stability of the optical source.

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