Demonstration of Photonic Integrated RAU for Millimetre-wave Gigabit Wireless Transmission

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Abstract—**This work reports the performance of a wireless transmission link based on a radio access unit (RAU) implemented in photonic integrated circuit (PIC) form. The PIC contains a high speed photodiode for direct optical to RF conversion, monolithically integrated with a semiconductor laser, used as an optical local oscillator for up-conversion of the incoming 16-QAM-OFDM signal through heterodyning. Wireless transmission was demonstrated with a spectral efficiency as high as 3 bits/s/Hz at 60 GHz carrier and with 1.2 Gb/s transmission rate. Moreover, the RAU based on a broad bandwidth photodiode integrated with a tuneable laser allowed for a compact unit that could operate at carrier frequencies up to 100 GHz.**

Keywords — photonic integrated circuit; millimetre-wave wireless transmission

I. Introduction

The license-free bandwidth available for generic 60-GHz radio worldwide spans up to 9 GHz (57−66 GHz in Europe and Australia, 57–64 GHz in the U.S. and Canada, 59–66 GHz in Japan). This large licence-free bandwidth can be exploited to offer potential multi-Gbit/s wireless connectivity. Operation in the 60-GHz band permits the use of antennas which not only have high gain (up to 40 dBi) [1], but are also much smaller than those used in the lower frequency bands. This enables multiple-input multiple-output (MIMO), beam forming and beam steering, which enhances the channel capacity and also supports non-line-of-sight (NLOS) communications. There have been a number of standardization efforts and industry alliance formations including WirelessHD, ECMA-387, IEEE 802.15.3c, and WiGig aimed at promoting 60-GHz technology to support multi-Gbit/s wireless communications. In recent years, this has resulted in some purely electronic consumer products based on 60-GHz radio technology being introduced in the market. However, some challenges in achieving full-scale commercialization remain, especially in providing broadband wireless and robust 60-GHz products.

An alternative solution is based on the photonic approach, which allows the optical signal first to be distributed with very little loss over optical fibre and afterwards converted to the mm-wave electrical domain through optical heterodyning. This photonic-based technique is, for instance, investigated within the scope of the IPHOBAC-NG project [2], which also supports different photonic applications for 60-GHz technology. For the next generation outdoor wireless infrastructure based on small cells to enhance 3G or 4G capacity and coverage, the networks would require higher capacity, reliability and cost-effective backhaul links to the core network. The deployment will require interference management between micro and macro cells and low opex. Millimetre wave based backhaul has an advantage over traditional copper/fibre based leased infrastructure, as most of the link is owned infrastructure, thereby reducing the opex. Generally capex vs opex ratio is about 10 to 90 in such deployments and hence mm-wave based backhaul drastically cuts expenditure. V-Band spectrum has frequencies 57-64 GHz which are globally unlicensed and approved for use, hence a good candidate for worldwide roll out. However, 60 GHz does come with its own problems of range due to high path loss and pronounced oxygen absorption after 100 metres. For the same transmit power, 60 GHz has less range and penetration compared to 5 GHz. This shortcoming can be turned into an advantage as we are talking about small cells. This natural coverage limitation when combined with narrow beams can provide security, low-interference and frequency reuse in neighbouring cells. With the soaring success of 4G, the current wireless network infrastructure backhaul capacity is getting constricted. Before the advent of 5G technology, this issue needs to be resolved to meet future bandwidth requirements.

The experimental demonstration presented in this paper addresses the future mobile network requirements with a novel concept of coherent photonic integrated remote antenna units by taking an advantage of the recent advances in photonic component integration. The monolithic integration of the photonic part of the RAU leads to smaller size and more importantly fewer packaging and alignment issues.

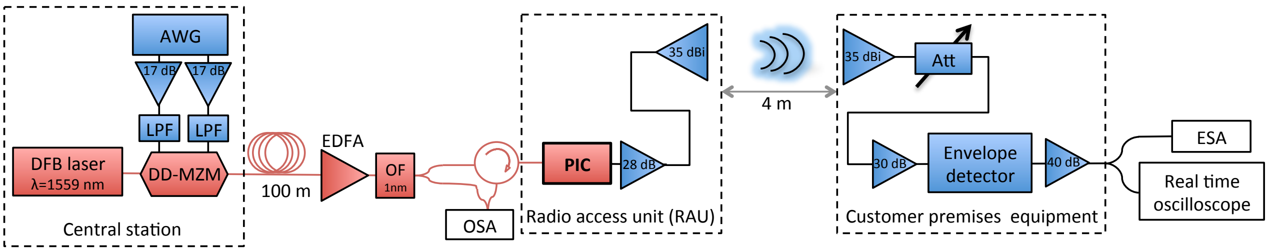

Fig. 1 Schematic of the experimental assembly of the 60 GHz wireless transmission link consisting of central station unit where OFDM data is modulated on single optical tone, a wireless transmitter based on monolithically integrated LO and optical-to-electrical converter, a wireless signal detection unit and monitoring equipment such as spectrum analyzers.

II. EXPERIMENTAL ARRANGEMENT

The experimental assembly used in the wireless transmission of the 60 GHz carrier signal is shown in Fig. 1. The single-mode laser operating at 1559.4 nm and capable of generating 15 dBm of optical power was externally modulated with an Orthogonal Frequency Division Multiplex (OFDM) signal using an external dual drive Mach-Zehnder modulator (DD-MZM) instead of IQ-modulator [3], providing optical single sideband signal (OSSB) [4]. The OFDM signals were generated in MATLAB and subsequently uploaded into an Arbitrary Waveform Generator (AWG). The output of the AWG was amplified by 17 dB and filtered using 7 GHz bandwidth low pass filter (LPF) before being applied at the RF ports of the DD-MZM [5]. All components related to the central station were located on one side of the building; hence the optical tone carrying the OFDM signal was transmitted through the building's optical fibre infrastructure (approximately 100 m of fibre) to the opposite side of the building where the photonic integrated RAU was situated. 0.3 dB total optical power loss was measured due to the signal transmission between "central station" and RAU, demonstrating the advantage of signal distribution over fibre.

The power level of the optical signal received after transmission over fibre was -3 dBm and needed to be amplified to compensate for the losses due to fibre splitters/couplers and inefficient coupling between lensed fibre and on-chip optical waveguide. Therefore an Erbium Doped Fibre Amplifier (EDFA) with 8 dB gain followed by a 1 nm bandwidth optical filter (OF) were used in the system. Subsequently the modulated signal was coupled into the optical waveguide on the PIC using an optical circulator connected to a lensed fibre with ~2 μm diameter spot size. The optical signal generated by the integrated DFB laser was coupled using the same lensed fibre and after the optical circulator could be observed on an optical spectrum analyser (OSA), together with the incoming optical carrier with modulated data. The usage of the optical circulator allowed control of the performance of the integrated laser as well as monitoring the frequency spacing between the two optical tones. The optical LO signal at 1558.8 nm together with the incoming signal with OFDM modulation are presented in Fig. 2, demonstrating frequency difference of 60 GHz.

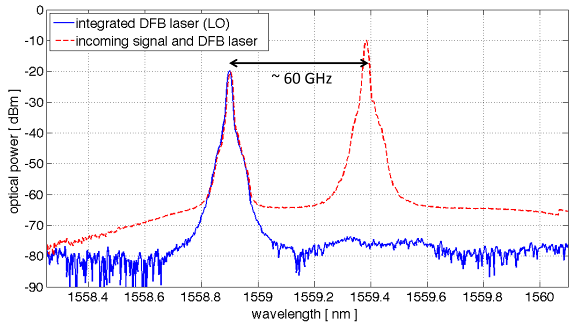

Fig. 2 Optical spectrum of the signal incoming from central office and the DFB laser (optical LO) integrated on the chip with UTC-PD.

Two optical signals were photomixed on one of the two integrated uni-travelling carrier photodiodes (UTC-PD) resulting in millimetre-wave signal being generated at the output of the UTC-PD coupled with coplanar waveguide (CPW) line which can be accessed through the ground-signal-ground high frequency probe. The generated millimetre-wave signal was amplified by a high power amplifier with 28 dB gain and afterward transmitted wirelessly using Cassegrain antennas with 35 dBi gain.

The receiving antenna was located at 4 m distance from the transmitter and was used to capture the OFDM signal converted to 60 GHz. Following the antenna, a variable value attenuator, set to provide at least 15 dB attenuation, was implemented to prevent the receiving amplifier from reaching the saturation point. It is expected that this attenuation could be removed and the transmission distance increased to 23 m, while maintaining high quality wireless transmission.

Once detected, the received signal was amplified using a broadband (50-67 GHz), low noise amplifier with 30 dB gain. After the amplifier the signal was down-converted using the envelope detector based on zero-biased Shottky diode suitable to operate within the V-band (50-75 GHz). The signal at an IF frequency of around 350 MHz was once more amplified and split to be observed on an electrical spectrum analyser and real time oscilloscope. Finally, the data set was acquired on a 50 GS/s sampling rate oscilloscope and further processed offline in MATLAB. The electrical spectrum of 60 GHz carrier and 16-QAM-OFDM data occupying 380 MHz bandwidth are presented in Fig. 3.

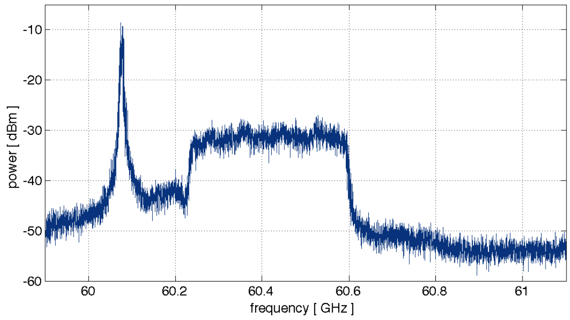

Fig. 3 Electrical spectrum of the 60 GHz carrier and OFDM data measured at the receiver at the input to the envelope detector (RBW= 1MHz, VBW=50kHz).

A 350 MHz offset was introduced between the 60 GHz carrier and the centre of the data envelope in order to mitigate the effect of the subcarrier-signal beat interference [6].

III. Photonic Integrated Circuit

The InP-based PIC used in the RAU of the transmission link has the advantage of having a broad-bandwidth photodiode and DFB lasers monolithically integrated on a single PIC measuring 0.7 mm x 4.4 mm. In fact, the PIC shown in Fig. 4 is the first reported chip containing two lasers monolithically integrated with fast photodiodes with a 3-dB bandwidth estimated to be 100 GHz [7] [8] and was designed to generate the mm-wave signals photonically through heterodyning [9].

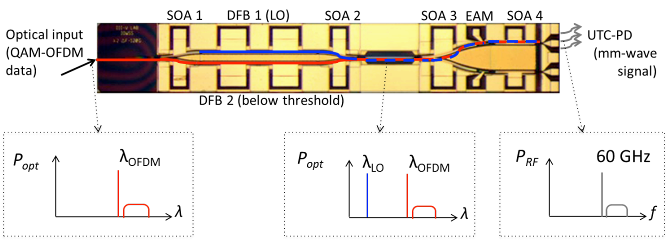

Fig.4 Photograph of photonic integrated circuit and schematic illustration of presence of optical tones along the chip.

In this paper we demonstrate the use of this PIC as an integrated photonic local oscillator in a RAU for down-conversion of the optical carrier to a millimetre wave carrier. To that purpose, in the discussed experiment only one of the integrated lasers is used to provide an optical local oscillator (LO) operating around 1558.9 nm when driven with 115 mA gain section current. The second laser is not lasing and only small current of less than 16 mA is applied to the gain section contact of the second integrated laser. This level of current is below the laser threshold, but allows minimising the optical waveguide propagation losses while the OFDM signal is guided on the chip. Both integrated lasers are 1.1 mm long and are characterised by FWHM linewidth in the MHz range. The LO laser can be continuously tuned through current injection to the laser gain section over more than 0.4 nm ,as shown in Fig. 5 and the laser current tuning sensitivity was measured to be -1.75 GHz/mA. Other than the DFB lasers and UTC-PD, the chip contains eight semiconductor optical amplifiers (SOA), two electro-absorption modulators (EAM) as well as passive components, such as couplers and waveguides, all indicated in Fig. 4 and described in more details in [10].

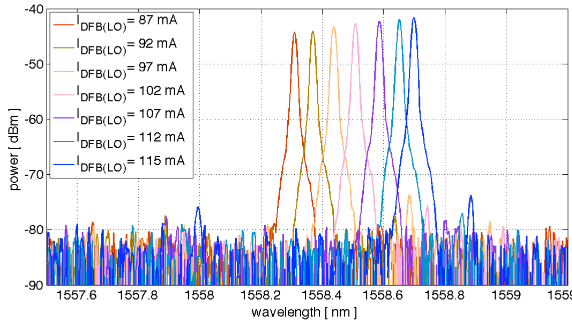

Fig. 5 Optical spectra of the integrated DFB laser showing tuneability over 0.4 nm.

The optical power delivered to the UTC-PD can not be measured directly, however the 60 GHz signal measured at the output of a CPW probe was at a level of -35 dBm when the integrated laser was driven with 115 mA of gain current and the optical power of the signal at the input of the lensed fibre was -3 dBm. The photodiode was biased at – 1.5 V and 1 mA of photocurrent was measured. Moreover, it should be mentioned that during the measurement the following currents were applied to the electrical contacts on the PIC: I_{SOA1}=10 mA, I_{DFB} = 16 mA, $I_{DFB(LO)}$ = 115 mA, $I_{SOA2(LO)}$= 9 mA, $I_{SOA2(OFDM)}$= 16 mA I_{SOA3}= 26 mA, I_{EAM} = 5 mA, I_{SOA4}= 27 mA. The PIC temperature was maintained at 20.5 ^{o}C using a Peltier cooler.

IV. Discussion and Transmission Results

In most radio-over-fibre (RoF) links, cost-effectiveness is the primary requirement, coupled with low power consumption. To achieve this, the optical complexity of the transceiver architecture needs to be minimized using low-cost and low-complexity optical and electrical components. The OSSB generation system used a DD-MZM instead of an IQ-modulator due to its simpler structure, a smaller footprint, and lower optical loss. At the receiver, an envelope detector is used due to its simplicity and low-cost. With the high frequency mm-wave systems, it is expected that the use of high sampling rate digital-to-analogue converters (DACs) and analogue-to-digital converters (ADCs) will be acceptable in future low-cost systems, as the performance of silicon complementary metal oxide semiconductor technology continues to increase, whereas the cost and power consumption reduce. Hence in our experiments, the data was encoded using OFDM modulation technique which is a key technology employed in broadband wireless systems. 16-QAM modulation format with 256 sub-carriers and 380 MHz bandwidth was used, allowing for spectral efficiency of 3 bits/s/Hz. Although for this work a single band of OFDM signal was used, the 7 GHz modulation bandwidth capability of the system, limited by the V-band components, can accommodate 15 such bands resulting in data rates higher than 10 Gbps in principle. The use of multiple bands can also allow future flexibility in bandwidth allocation to end-users depending on the network topology.

To evaluate the performance of the wireless transmission link the received signal has been plotted as a constellation diagram presented in Fig. 6, showing that each symbol can be clearly distinguished. The received wireless 16-QAM-OFDM was characterized to have a SNR better than 20 dB and the average frame EVM RMS was -21.43 dB. This corresponded to a received signal BER of 1.27 10^{-4}.

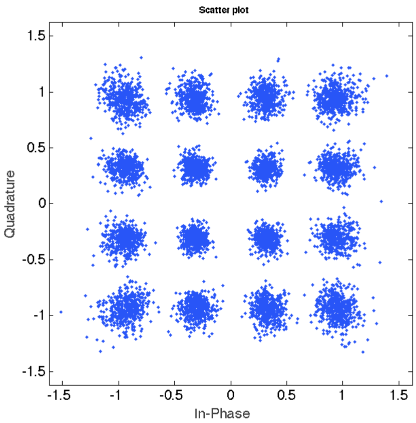

Fig.6 16-QAM-OFDM constellation obtained after 100 m on fibre and 4 m wireless transmission.

V. Conclusions

In this paper we present another application of a photonic integrated circuit primarily developed as an integrated mm-wave source. We demonstrated a 60 GHz 1.2 Gb/s wireless transmission over 4 m air link that can be increased to over 23 m of transmission distance simply by removing 15 dB attenuation which was introduced to the system. The system architecture uses a RAU based on a photonic integrated circuit containing a DFB laser monolithically integrated with a broad bandwidth photodiode. The integrated laser is used as a local oscillator which can be continuously tuned over more than 0.4 nm. This corresponds to 50 GHz of the frequency agility for the photonic part of the RAU. Moreover the use of a 16-QAM-OFDM modulation format together with broadband envelope detector makes the system less sensitive to the frequency and phase changes associated with free running lasers. The use of the monolithically integrated photonic components in a RAU offers a clear advantage in terms of overall size and packaging of the unit.

Acknowledgment

This work has been supported by the European Commission through the IPHOBAC-NG and iPHOS projects (grant agreements no: 619870 and 257539, respectively).

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