A Novel mmW A-RoF Transmission Scheme Employing Dual-stage Active Demultiplexing of an Optical Frequency Comb

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Abstract *A simple, highly efficient scheme of generating mmW signals, employing an optical frequency comb and a dual-stage active demultiplexer is proposed. We experimentally demonstrate the generation and distribution of 38 GHz 64-QAM UF-OFDM signal over 25 km of fibre, achieving a BER of 1.6 e^{-4}.*

Introduction

5G, with its massive bandwidth and very low latency, promises to revolutionise the telecommunication landscape. It will provide the necessary infrastructure for next generation services such as autonomous vehicles, telesurgery, smart cities, Industry 4.0, etc. In order to reap the benefits of this new paradigm, network operators need to build a network infrastructure capable of supporting the stringent transmission requirements, both in the wired and wireless domains. Due to spectral congestion in the microwave part of the radio spectrum, transmission of ultra-broad bandwidth data requires the usage of millimetre-wave (mmW) frequencies (28 GHz and above), where large spans of un-allocated spectrum are available. Recently, ITU listed higher frequency bands around 28, 38, 60 and 73 GHz for future 5G implementation [1]. Moving towards such high carrier frequencies, together with the push toward increased capacity, requires a drastic reduction in the cell size, especially in densely populated areas. This in turn implies that a large number of cells need to be deployed, to provide sufficient coverage. As a result, the minimization of cell cost is crucial for the fast roll-out of 5G networks operating at mmW frequencies. The use of the centralized or cloud radio access network (C-RAN) scenario [2] together with analog radio over fiber (A-RoF) [3] is a promising candidate to minimise the cost and complexity, and to achieve a high spectral efficiency of the 5G distribution network.

In this article, we propose a novel simple approach of mmW generation for an A-RoF transmission system. This technique is based on the optical heterodyning of optical frequency comb (OFC) tones filtered and modulated using a dual-stage active demultiplexer. The demultiplexing scheme is based on optical injection locking. We have previously characterised a single active demultiplexer [4] and demonstrated mmW generation employing such architecture [5]. Such schemes benefit from the generation of a high purity mmW signal stemming from the OFC's fixed frequency spacing and high level of phase correlation [6]-[8]. However, a unique feature of the dual-stage active demultiplexer, proposed in this paper, is that it does not require the use of optical splitters and combiners, as both optical tones, used for the mmW generation, traverse the same path. This improves the energy efficiency of the transmitter and alleviates the challenges introduced by path length mismatch. The latter renders the transmitter highly tolerant to the optical linewidth of the OFC [9]. Furthermore, the proposed configuration eliminates the need for a lossy external modulator [8]. Another benefit, an inherent feature of the active demultiplexer [4], is the amplification of the comb tones. Hence, there is also no need for an optical amplification stage (EDFAs or SOAs) nor ASE filters. The proposed method is also highly flexible in terms of the choice of the generated mmW frequency. Finally, the novel scheme lends itself to photonic integration, providing a path towards further cost, footprint and energy consumption reduction.

In this paper, we experimentally demonstrate generation of 38 GHz A-RoF 64 QAM universal filtered OFDM (UF-OFDM) signal using the proposed transmitter. We characterise the generated mmW carrier in terms of the power, frequency and linewidth, and demonstrate a highly stable performance. Furthermore, we transmit the generated signal over 10 and 25 km of standard single mode fibre (SSMF), achieving a bit-error rate (BER) of 6.3e^{-5} and 1.6e^{-4} respectively.

Principle of operation

The schematic of the proposed transmitter is shown in Fig. 1(a) (green box). It consists of an OFC, generating highly coherent tones, followed by a semiconductor laser based dual-stage active demultiplexer. A spectral line graph, illustrating the principle of operation of the transmitter, is shown in Fig. 1(b). The output of the OFC is

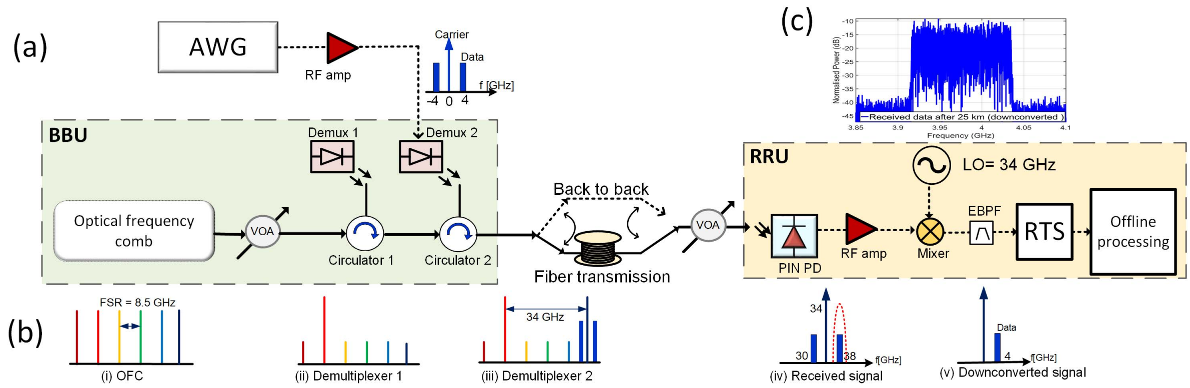

Fig. 1: (a) Experimental setup of the A-RoF transmission system employing dual-stage active demultiplexer, (b) line-graph illustration of the principle operation, (c) electrical spectrum of the downconverted UF-OFDM data after 25 km fibre transmission. BBU: baseband processing unit; RRU: remote radio unit; VOA: variable optical attenuator; AWG: arbitrary waveform generator; PD: photodetector; EBPF: electrical band pass filter; LO: local oscillator; RTS: real time oscilloscope.

injected, via an optical circulator, to the first stage of the demultiplexer (Demux 1), whose wavelength is then tuned (using the bias current and the temperature) to match the wavelength of the desired comb line. Once the alignment is achieved, Demux 1 becomes injection locked by the comb line. As a result, Demux 1 inherits the frequency and phase characteristics of the OFC, while at the same time amplifying the selected comb tone (the power of Demux 1 is much higher than that of the comb line) [4]. The remaining, spurious OFC tones also pass through Demux 1, but without any amplification. We define the difference between the power of the demultiplexed and the remaining comb tones as the comb line suppression ratio (CLSR). While the power of these spurious tones is low, it is sufficient to enable a stable injection locking of the second demultiplexing stage (Demux 2). Therefore, a second OFC tone can be demultiplexed, by injecting the output of Demux 1 into Demux 2. The wavelength of the latter is then tuned to match that of a spurious comb tone, separated from the tone selected by Demux 1, by a frequency of the mmW signal that is to be generated. As a result, Demux 2 is injection locked by this second comb tone, thus also inheriting the spectral characteristics of the OFC and providing amplification to the selected comb tone. Hence, the output of Demux 2 consists of the two selected high power spectral components (tone selected by Demux 1 and 2), separated by the desired mmW frequency. Finally, since the active demultiplexer is a standard semiconductor laser, we can imprint the electrical data that is to be transmitted on the mmW signal, by directly modulating Demux 2.

A-RoF system based on dual-stage active demultiplexer

The experimental setup of the proposed A-RoF system based on dual-stage active demultiplexer is shown in Fig. 1(a). It emulates the baseband processing unit (BBU) and a remote radio unit (RRU) connected by a length of fibre.

The OFC, with a free spectral range (FSR) of 8.5 GHz and an average power of 7 dBm, is generated using an externally injected gain-switched laser (EI-GSL) [10]. Two commercially available discrete-mode lasers (with threshold currents of 12 mA) are used as demultiplexers. The comb line power, injected to Demux 1, is adjusted to -26 dBm using an inline VOA. The optical spectrum of the OFC, after the VOA, is shown in Fig. 2 (a). Demux 1 is tuned to select the 1549.92 nm comb tone, achieving a CLSR of 32 dB and an output power of 7 dBm. Next, the output of Demux 1 is injected into Demux 2 and

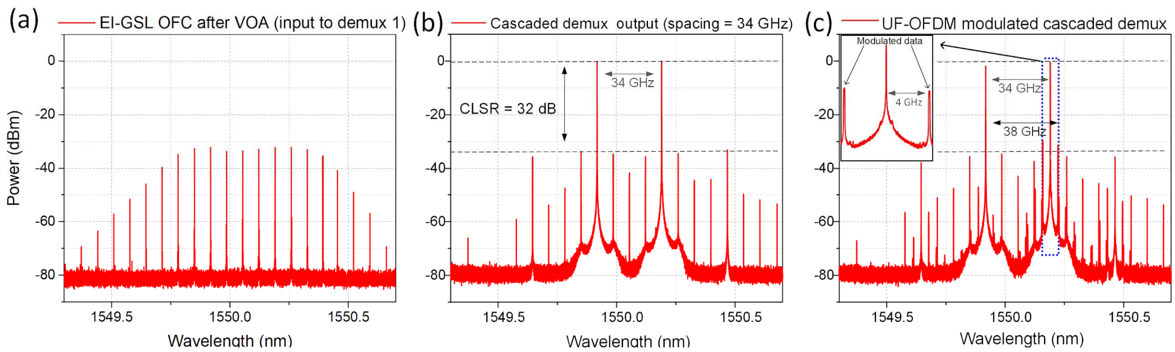

Fig. 2: Optical spectra of (a) EI-GSL OFC with FSR of 8.5 GHz after a VOA (input to demux 1), (b) Demux 2 output showing the selected and amplified tones separated by 34 GHz, (c) Demux 2 output directly modulated with the UF-OFDM data.

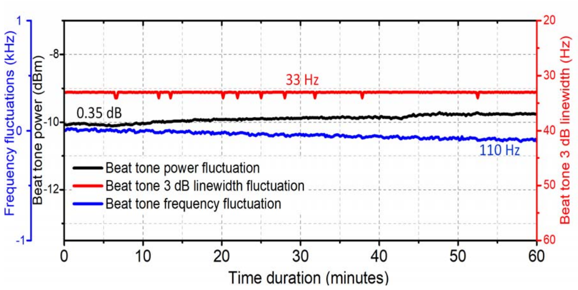

Fig. 3: Stability test of the dual-stage demultiplexer, showing the beat tone: power (black), frequency (blue) and linewidth (red) fluctuations over 60 minutes period

the wavelength of the second device is tuned to the comb tone with a wavelength (in this case 34 GHz) higher than that of Demux 1. The optical spectrum of Demux 2, showing the two filtered comb tones, is depicted in Fig. 2(b). The stability of the dual-stage demultiplexer is tested, by beating the two modes on a photodiode (PD) and measuring the power, frequency and the linewidth of the generated mmW carrier over a period of 60 minutes. From the plots shown in Fig. 3, it can be seen that the power of the generated mmW signal is very stable, exhibiting a maximum fluctuation of 0.35 dB. This is a result of both optical tones traversing the same path, which eliminates any path length or polarisation variations. Furthermore, the plots of the frequency fluctuation, (~110 Hz originating from the RF source used in OFC generation) and the linewidth of the beat tone (~33 Hz) indicate that a stable injection locking of both demultiplexing stages is achieved, ensuring a constant frequency separation between the optical tones and the transfer of the OFC phase noise to the demultiplexer (maintaining phase correlation).

To complete the A-RoF system test, we directly modulate Demux 2 (biased at $5.5 \times I_{th}$, output power 7.5 dBm) with 64 QAM UF-OFDM data. It comprises 76 subcarriers upconverted to 3.98 GHz, with a total data bandwidth of 112 MHz, subcarrier baud rate of 1.4 MBaud and a total data rate of 0.67 Gb/s. The optical spectrum of the Demux 2 output, after modulation, is shown in Fig. 2(c). The signal from Demux 2 is then sent to the RRU. At the RRU, the optical signal is detected on a PD, either directly (for the back-to-back (BtB) test) or after transmission over SSMF. The beating of the optical tones on the PD results in the generation of three main mmW components: a 34 GHz unmodulated carrier and two data signals upconverted to 30 and 38 GHz (as depicted in the line graph in Fig. 1(b(iv)). The output of the PD is then amplified, and the 38 GHz data signal is downconverted to 4 GHz, using a mixer and a 34 GHz signal from a local oscillator. The 4 GHz signal is then filtered, using an electrical band-pass filter, and captured using a RTS operating at 40 GS/s. Finally, the offline processing, such as re-sampling, timing synchronization, phase estimation, error vector magnitude (EVM) and BER measurements, is performed offline.

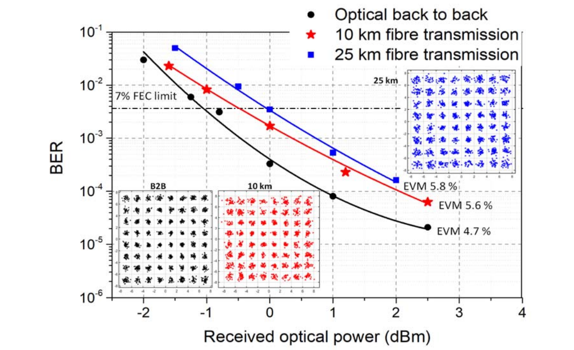

Fig. 4: BER vs received optical power. Insets show the constellation diagram for the BtB (black) as well as 10 km (red) and 25 km (blue) fibre transmission case.

Tab. 1: A-RoF system performance

	BtB	10 km	25 km
BER	$2.1\ e^{-5}$	$6.3\ e^{-5}$	$1.6\ e^{-4}$
EVM	4.7%	5.6%	5.8%

To verify the performance of the proposed scheme, we carried out BER vs. received optical power measurements for three cases: (i) BtB (black), (ii) 10 km (red) and (iii) 25 km (blue) SSMF fibre transmission. The results are plotted in Fig. 4, with the summary of the results shown in Tab. 1. For all three cases, a BER below the FEC limit of $3.8\ e^{-3}$ (EVM < 8%) is achieved. This highlights the ability of the proposed transmitter to generate stable, high quality mmW signals.

Conclusions

We have experimentally demonstrated a 25 km transmission of a 38 GHz 64 QAM UF-OFDM signal generated using a novel transmitter based on an OFC and a dual-stage active demultiplexer. Unlike other OFC-based schemes, the proposed architecture features a single optical path, alleviating the need for optical splitters, combiners, an external modulator as well as careful path length matching mechanisms. Furthermore, the inherent amplification provided by the active demultiplexer, removes the requirements for an external optical amplifier. As a result, the proposed scheme offers a significant cost, complexity and footprint reduction. Finally, as all the components of the transmitter can be realised in InP, the entire device can be realised within a single photonically integrated chip, providing further cost and footprint savings.

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