Optical Linewidth Tolerant mmW Generation Employing a Dual-Stage Active Demultiplexer

Prajwal D. Lakshmijayasimha, Aleksandra Kaszubowska-Anandarajah, *Senior Member, IEEE*, Syed Tajammul A., Eamonn P. Martin, and Prince M. Anandarajah, *Senior Member, IEEE*

***Abstract*— In this letter, we propose a novel linewidth tolerant millimetre-wave (mmW) generation scheme employing a dual-stage active demultiplexer and an optical frequency comb (OFC). A unique feature of this architecture is that the two heterodyned tones travel the same path, alleviating the challenges associated with mismatches in the path lengths. We analyse the influence of the path length difference and source linewidth on the purity of the generated mmW signal and verify the tolerance, of the proposed scheme, to the optical linewidth. In addition, an experimental investigation of the performance of a 64 QAM discrete multitone (DMT) analog-radio over fibre (A-RoF) distribution system operating at 37.5 GHz using the proposed architecture, is presented. A BER below the HD-FEC limit is achieved, after 25 km fibre transmission, when employing an OFC with linewidth of ∼30 kHz and ∼3.1 MHz. Moreover, no significant performance penalty (at the HD-FEC limit) is observed due to an increase in the OFC linewidth, highlighting the linewidth tolerance of the proposed system.**

***Index Terms*— Optical frequency comb, millimetre-wave, active demultiplexers, optical injection locking, radio-over-fibre.**

I. Introduction

Wireless communications is progressing towards 5^{th} generation and beyond (5G+), which promises to provide higher capacity, higher data rate, and lower latency connectivity. Such networks are envisioned to support next-generation services including ultra-high definition (UHD) 4/8K online streaming and gaming, autonomous vehicles, virtual reality, Industry 4.0, etc [1]. To reap these benefits, network providers need to build an innovative and technically advanced infrastructure, capable of handling stringent transmission requirements, in both the wired and wireless domains. A key enabling technology for 5G+ that can offer large capacity, high data rates and low latency, entails the use of millimetre wave (mmW) frequencies (from 26 GHz to 300 GHz). For effective utilisation of the un-allocated mmW spectrum, ITU-R considers frequency bands around 28, 38, 73 GHz for future 5G+ implementations [1]. While operations transition towards such high frequencies, efficiency in terms of spectral usage, cost and power consumption will be crucial. Hence, the use of a centralised radio access network (C-RAN) along with analog radio over fibre (A-RoF) is considered to be an attractive solution for 5G+ [2].

A-RoF relies on photonic mmW generation schemes, based on coherent heterodyning of two optical tones, and exploits the benefit of using mature, high-bandwidth, low loss, off-the-shelf optical components. There are several methods of generating the optical tones, including the use of an optical frequency comb (OFC) [2]–[4], frequency doubling [5], dual-mode fibre laser [6], etc. The use of an OFC allows the generation of high-quality mmW signals (excellent frequency stability and low phase noise) with a potential reduction in cost. These benefits stem from the OFC's precise frequency spacing and a high degree of phase correlation between the tones. When using an OFC, the required two tones, separated by the desired frequency, need to be filtered out, using either traditional solutions such as arrayed waveguide gratings, wavelength selective switches, or laser-based active demultiplexers [2], [7]. The latter operates on the principle of optical injection locking (OIL) and offers the combined functionality of a tunable filter, ultra-low noise amplifier, power equaliser, and a modulator, all in a single device [8].

The major limitation of the demultiplexing approaches mentioned above stems from the fact that they send the selected tones over different paths, one of which typically includes a modulator, before recombining and transmitting them over the fibre. Thus, the split tones experience different path lengths and as a result, different time delays, which introduce a random phase walk-off between the tones. When heterodyned, this phase walk-off leads to degraded spectral quality of the generated mmW signal, as analysed by T. Shao *et. al.,* in [9]. Thus, the difference in the time delay needs to be compensated by adding tunable optical delay lines (ODL), path length matching fibre, or a phase noise-cancelling receiver [3], [9], which increases the complexity of the system. The impact of the random phase walk-off becomes more severe as the linewidth of the optical tones increases. To overcome these drawbacks, in [4] we proposed the use of a dual-stage active demultiplexing for the generation of an mmW signal. The unique feature of this scheme is that both comb tones, used for heterodyning, traverse the same path. This alleviates the challenges associated with path length matching and in turn, offers improved tolerance to OFC linewidths. Furthermore, it eliminates the need for an optical splitter and combiner, thus increasing the power budget of the system. In addition, as the scheme is based on an active demultiplexer, it benefits from the multifunctionality mentioned earlier, (eliminating the need for an external modulator and optical amplifier) thereby rendering

Manuscript received January 28, 2022; revised February 25, 2022; accepted March 30, 2022. Date of publication April 11, 2022; date of current version April 18, 2022. This work was supported in part by the Science Foundation Ireland under Grant 15/CDA/3640, Grant 13/RC/2077_P2, and Grant 18/RI/5755; and in part by the Disruptive Technologies Innovation Fund (DTiF) under Grant DT20180268. *(Corresponding author: Prajwal D. Lakshmijayasimha.)*

Prajwal D. Lakshmijayasimha, Syed Tajammul A., Eamonn P. Martin, and Prince M. Anandarajah are with the Photonics Systems and Sensing Laboratory, School of Electronic Engineering, Dublin City University, Dublin 9, D09 DXA0 Ireland (e-mail: prince.anandarajah@dcu.ie).

Aleksandra Kaszubowska-Anandarajah is with the CONNECT Centre, Dunlop Oriel House, Trinity College Dublin, Dublin 2, D02 PN40 Ireland (e-mail: anandara@tcd.ie).

Color versions of one or more figures in this letter are available at https://doi.org/10.1109/LPT.2022.3166254.

Digital Object Identifier 10.1109/LPT.2022.3166254

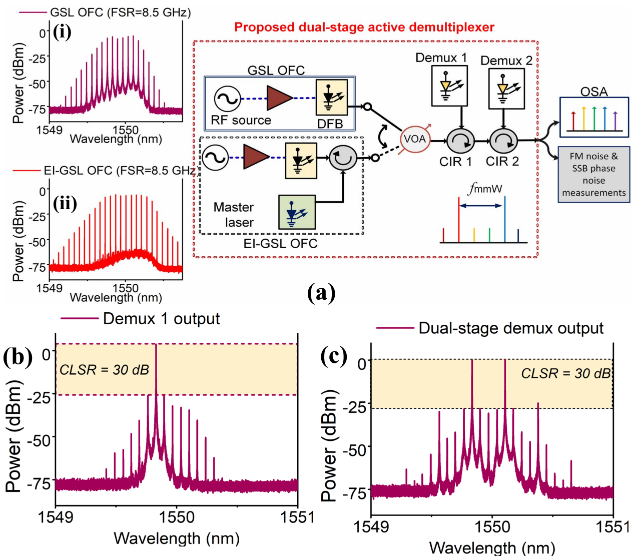

Fig. 1. (a) Experimental setup of the proposed mmW generation scheme employing a dual-stage active demultiplexer. Inset: an optical spectrum of the generated (i) GSL OFC, (ii) EI-GSL OFC with an FSR of 8.5 GHz. Optical spectra of (b) Demux 1 output, and (c) dual-stage demultiplexer output. Here, VOA: variable optical attenuator; CIR: circulator;. OSA resolution: 20 MHz.

the transmitter to be simple and cost-effective. Finally, the proposed architecture can be photonically integrated, which can further reduce the cost, footprint, and energy consumption.

In the previous work [4], we showed the tunability and stability of the proposed mmW generation method. We have also demonstrated the use of the proposed scheme in an A-RoF system operating at 38 GHz and carrying universally filtered (UF)-OFDM signals. In this work, we carry out a thorough investigation of the impact of the OFC linewidth on the quality of the generated mmW signal and the performance of a 5G system using 64-QAM discrete multitone (DMT) signalling. Hence, we examine the use of two OFC sources (i) a gain-switched laser (GSL), and (ii) an externally injected GSL (EI-GSL) with optical tone linewidths of 3.1 MHz, and 30 kHz, respectively. Firstly, we present the operational principle of the proposed scheme and characterise the mmW signals generated. Subsequently, we analyse the impact of path length mismatch and optical source linewidth on the quality of the resultant mmW signal. Finally, a complete A-RoF system, for the distribution of a 37.5 GHz directly modulated 64-QAM DMT signal over 25 km of standard single-mode fibre (SSMF) is realised. The system performance is evaluated for two different source linewidths. A bit error rate (BER) below the 7% hard-decision forward error correction (HD-FEC) limit is achieved in both cases demonstrating the high tolerance of the proposed scheme to the optical linewidth of the source.

II. Proposed mmW Generation Scheme

A. Operation Principle: Dual-Stage Active Demultiplexer

The experimental setup of the dual-stage active demultiplexer based mmW generation is shown in Fig. 1(a). It comprises an OFC, generating phase correlated tones, followed by two semiconductor lasers in series, used as a dual-stage active demultiplexer. It is important to mention that the proposed scheme is compatible with any type of OFC. In this work, two versions of a gain-switched laser (GSL) are considered; (i) GSL (no external injection), which generates an OFC with a large linewidth (usually few MHz), and (ii) an externally injected (EI)-GSL that generates an OFC with a low linewidth (typically in kHz).

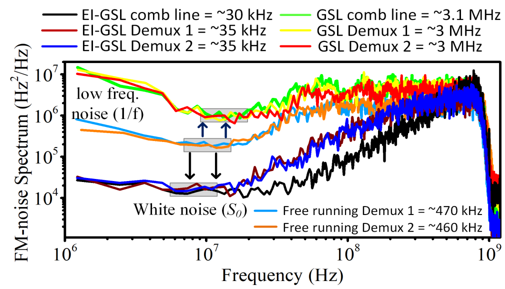

Fig. 2. FM-noise spectra of the dual-stage active demultiplexer.

Firstly, a single-mode DFB laser (threshold current I_{th} of ~12 mA) is biased at 51 mA and gain-switched (GS) with a sinusoidal signal with a frequency of 8.5 GHz and a power of 21 dBm. The optical spectrum of the generated GSL OFC with a free spectral range (FSR) of 8.5 GHz, is shown in the inset (i) of Fig. 1(a). It consists of 6 tones within 3 dB from the spectral peak and exhibits an optical carrier to noise ratio (OCNR) of 50 dB (20 MHz OSA resolution). Secondly, the GSL laser is externally injected with a tunable laser acting as a master laser to realise EI-GSL OFC (OCNR $>$ 55 dB) is shown in the inset (ii) of Fig. 1(a). Next, two commercially available semiconductor discrete mode (DM) lasers are chosen as the dual-stage active demultiplexer. These DM lasers, with a threshold current (I_{th}) of 10 mA, emit light with an output power of 7.5 dBm (Demux 1) and 8 dBm (Demux 2) when biased at $\sim 5 \times I_{th}$. The output of the OFC is injected into Demux 1 via a circulator (CIR). The comb line power (CLP) is set to −25 dBm with the aid of an inline variable optical attenuator (VOA). Demux 1 is temperature tuned to match the wavelength of the desired comb tone and subsequently injection-locked by the comb tone to enable its demultiplexing, with a comb line suppression ratio (CLSR) of 30 dB, as shown in Fig. 1(b). Due to OIL, Demux 1 inherits the frequency and phase characteristics of the OFC [4]. In addition, the demultiplexed tone is de-facto amplified, since the output power of Demux 1 is much higher than the input CLP [2]. The operational limits of the active demultiplexer and the influence of the injection locking parameters on the CLSR and phase noise of the demultiplexer can be found in [8]. The same characterisation and OIL conditions hold good for the proposed dual-stage active demultiplexer as well. Next, the output of Demux 1 is injected into Demux 2 and the wavelength of Demux 2 is tuned and injection-locked by an unsuppressed comb tone, which is separated by the desired mmW frequency (in this case 34 GHz) from the Demux 1 wavelength. Here again, the OIL of Demux 2 results in the transfer of the frequency and phase of the comb tone to Demux 2. Hence, as shown in Fig. 1(c), the output of Demux 2 consists of two amplified highly correlated tones, separated by 34 GHz and with a CLSR of 30 dB. Subsequently, the output of Demux 2 is heterodyned on a photodetector (PD), which results in the generation of a high purity mmW signal. It is important to mention that, Demux 2 acts as a mirror for the demultiplexed tone from Demux 1. Hence, the power levels of the two tones at the output of Demux 2 are similar and depend on their biasing conditions.

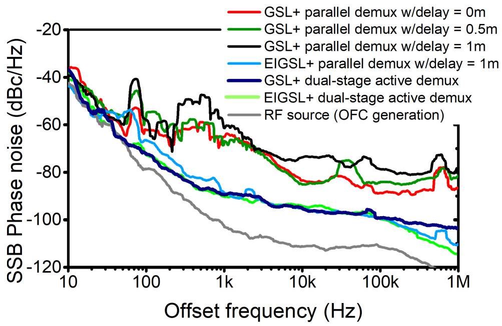

Fig. 3. Single sideband (SSB) phase noise characterisation of the generated 34 GHz mmW signal.

B. Phase Noise Transfer

The phase noise transfer from the OFC to the demultiplexed tones is verified by characterising the FM noise spectrum, using a modified delayed self-heterodyned technique [10]. The measured FM noise spectrum $S_F(f)$, describes the power spectral density of the instantaneous frequency fluctuations. The Lorentzian shaped optical linewidth (δf) can be retrieved from the white (flat) noise component (S_0), given by $\delta f = \pi \times S_0/2$ [10]. The results of the FM noise spectrum measurements, for various cases, are shown in Fig. 2. Firstly, we characterise the phase noise of a filtered tone (using a passive filter) from the GSL and EI-GSL, and the free running (FR) Demux 1 & 2. The optical linewidths are measured as ~3.1 MHz (GSL tone), 30 kHz (EI-GSL tone), 460 kHz (FR Demux 1) and 470 kHz (FR Demux 2). Subsequently, we demultiplex two tones that are separated by 34 GHz from the GSL and EI-GSL, using the proposed dual-stage active demultiplexer. The optical linewidth of the GSL tones is passed onto the injection locked Demux 1 and 2, resulting in the increase in their linewidths to ~3 MHz. Similarly, a pair of EI-GSL lines are demultiplexed, reducing the linewidth of the injection locked Demux 1 and 2 to ~35 kHz. In both cases, there is a clear indication of an efficient phase noise transfer from the OFC to demultiplexers through OIL.

C. Impact of Path Length Mismatch on the Quality of the mmW

Next, we investigate the impact of the optical linewidth (δf) and path length mismatch on the generated 34 GHz mmW signal by characterising its single sideband (SSB) phase noise. The achieved results are shown in Fig. 3. Firstly, we consider a scenario, where a pair of GSL comb lines (δf ~3.1 MHz) are filtered employing parallel active demultiplexers (split and recombine approach) [2]. The SSB phase noise, at a 10 kHz offset is measured as −83.5 dBc/Hz, as depicted by the red trace in Fig. 3. The observed phase noise deterioration is due to the path mismatch and to validate this claim, we subsequently introduce additional 0.5 and 1m fibre delays in one of the arms. On comparing the SSB phase noise (red, green, black traces) in Fig. 3, we can observe a significant deterioration in phase noise, for offsets >100 Hz due to the random phase walk-off induced by the path length mismatch between the two arms. Subsequently, the same procedure is repeated with the EI-GSL OFC (δf ~30 kHz). As seen in Fig. 3 (cyan trace), the additional delay path length of 1m has a negligible effect, resulting in the SSB phase noise of ~ −95.3 dBc/Hz (at 10 kHz offset). This can be attributed to the low linewidth of the optical tones having longer coherence length, thus a better tolerance to path length mismatch. The above findings attest to the stringent linewidth requirements needed to generate high purity mmW signals, when using two tones that traverse different paths. The SSB phase noise measurements are benchmarked with the RF source (at 8.5 GHz) used for the OFC generation (− 110 dBc/Hz). Finally, we consider the GSL comb (δf ~3.1 MHz) with the proposed dual-stage active demultiplexer. The SSB phase noise of the resultant 34 GHz mmW signal, at a 10 kHz offset, is measured as ~ −95.5 dBc/Hz, as illustrated in the blue trace in Fig. 3. The low phase noise signifies that the excellent phase correlation between the tones is maintained during demultiplexing/ mmW generation process. This is due to both filtered tones traversing the same path and not experiencing any walk-off. Thus, the proposed dual-stage active demultiplexer scheme enables generating a high purity mmW signal and provides a high tolerance to the OFC linewidth.

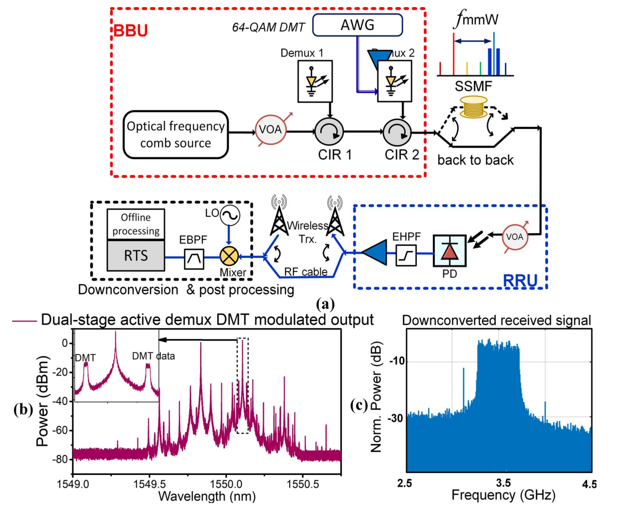

Fig. 4. (a) Experimental setup of the A-RoF system employing a dual-stage active demultiplexer, (b) optical spectrum of the dual-stage demultiplexer (GSL OFC) directly modulated with 64-QAM DMT (inset shows the enlarged view of the dotted area), (c) received 64-QAM DMT data signal, after 25 km transmission, downconverted to 3.5 GHz. Here, BBU: baseband processing unit; RRU: remote radio unit; AWG: arbitrary waveform generator; PD: photodetector; EHPF: electrical high pass filter; EBPF: electrical bandpass filter; LO: local oscillator; RTS: real-time oscilloscope.

III. Source Linewidth Tolerant A-RoF System

In this section, we demonstrate the source linewidth tolerance of the proposed dual-stage active demultiplexer, by evaluating its performance in an A-RoF distribution system. The experimental setup is designed to emulate a baseband processing unit (BBU) connected to a remote radio unit (RRU) with an optical fibre, as shown in Fig. 4(a). At the BBU, the OFC is followed by a dual-stage active demultiplexer to enable the two-tone selection and amplification.

Demux 2 is then directly modulated with the data to be transmitted on the mmW signal.A 64-QAM DMT signal is generated using a Micram arbitrary waveform generator operating at 25 GSa/s. It consists of 36 subcarriers (96 symbols/ subcarriers) upconverted to 3.5 GHz, with a total bandwidth of 450 MHz and the subcarrier baud rate of 12.5 MBaud, resulting in a raw data rate of 1.32 Gb/s. The data signal, with 1.8 Vp-p, is used to directly modulate Demux 2 that is DC biased at 51 mA. The optical spectrum of the directly modulated dual-stage active demultiplexer is shown in Fig. 4(b). The

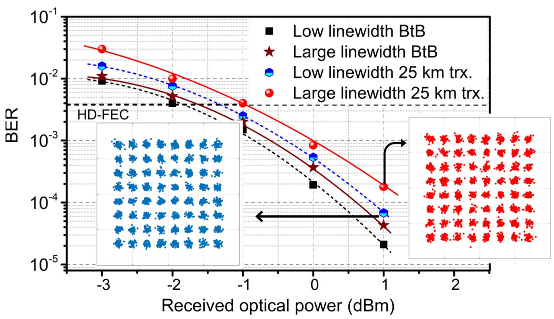

Fig. 5. BER vs received optical power for back-to-back (BtB) and 25 km transmission. Insets: the constellations at the indicated ROPs. Here, the solid and dotted curves are for 3.1 MHz and 30 kHz OFC linewidths, respectively.

TABLE I
A-RoF System Performance

OFC linewidth	BER at ROP = 1 dBm		Power penalty after 25 km trx. (at HD- FEC limit)
	BtB	*25 km trx.*	
δf = 30 kHz	2.1 x10^{-5}	6.8 x10^{-5}	0.5 dB
δf = 3.1 MHz	4.3 x10^{-5}	1.8 x10^{-4}	0.6 dB

output of Demux 2 is sent to the RRU through an optical fibre. At the RRU, the received signal is detected using a 50 GHz PD, followed by an RF amplifier. The PD generates three main RF frequencies: an unmodulated carrier and two data signals at frequencies 34 GHz ± 3.5 GHz. The upconverted mmW data signal can be then transmitted to the end-user via a wireless link. In this work, we focus our investigation on the optical link of the A-RoF system. Hence, the wireless link is replaced by an electrical RF cable. At the receiver, the desired data band (37.5 GHz) is downconverted to an intermediate frequency (IF = 3.5 GHz), by mixing it with an external local oscillator (LO) (as shown in Fig. 4(a)). The 3.5 GHz signal is then filtered using an electrical bandpass filter, captured using a real-time oscilloscope (RTS) operating at 40 GSa/s and post-processed (re-sampling, timing synchronisation and BER calculations) using MATLAB. The received downconverted data signal after 25 km SSMF is shown in Fig. 4(c).

To evaluate the impact of the OFC linewidths on the performance of the proposed A-RoF system, we measure BER as a function of the received optical power (ROP) for 64-QAM DMT signals at 37.5 GHz, over back-to-back (BtB) and 25 km fibre transmission. The above-mentioned tests were performed for OFC linewidths of 30 kHz and 3.1 MHz. From Fig. 5, it is evident that the BER is less than the 7% HD-FEC limit for all the cases. A summary of A-ROF system performance is shown in Table 1. After 25 km transmission (at ROP = 1 dBm), a small BER degradation is observed in the case of the larger linewidth. This can be attributed to the phase-to-intensity noise conversion caused by chromatic dispersion in the fibre. It is expected that for higher mmW frequencies or longer transmission distances this penalty will increase, placing an ultimate limit on the source (OFC) linewidth. On comparing the plots, for power required to achieve the FEC limit after 25 km transmission, we observe a penalty of ~0.5 dB and ~0.6 dB (w.r.t BtB) for the 30 kHz and 3.1 MHz linewidths, respectively. The fact that both OFC sources perform exceptionally well with the proposed scheme and suffer no performance penalty due to the increase in linewidth, highlights the linewidth tolerance of the proposed A-RoF system. It is important to mention that these results are achieved without employing any delay or phase compensation (hardware or software) and external optical amplifiers. Furthermore, the system results indicate improved performance in comparison to previous demonstrations employing phase compensation techniques [2], [9].

IV. Conclusion

In this letter, we have proposed a simple mmW signal generator employing a novel dual-stage active demultiplexing of OFC tones. We analyse the influence of the linewidth and the relative time delay between the optical tones used for the mmW generation. Furthermore, the performance of a 64-QAM DMT A-RoF distribution system, employing the proposed method, for two OFC linewidths of 30 kHz and 3.1 MHz is presented. A BER below the HD-FEC limit is achieved after 25 km SSMF transmission, for both cases. We show that the two orders of magnitude increase in optical linewidth of the source introduce a minimal penalty of 0.1 dB at the HD-FEC limit, verifying the linewidth tolerance of the proposed system. As a result, a cheap OFC with MHz linewidths can be used instead of an expensive high purity OFC source with kHz linewidths. In addition, the use of a dual-stage demultiplexer benefits from eliminating the optical splitter and re-combiner, tunable ODL or path matching fibre, optical amplifier and external modulator. This provides a minimum of 6 dB increase in the power budget (from split and recombine) that could be used to extend the system reach. Overall, the benefits of the proposed method, coupled with the possibility of photonic integration of the entire transmitter, can deliver a significant reduction in the cost, complexity, footprint and energy consumption of the systems, paving the way for rapid deployment of future 5G+.

References

[1] "IEEE 5G and beyond technology roadmap," IEEE, White Paper 1, 2017, pp. 1–39.
[2] S. T. Ahmad *et al.*, "Active demultiplexer enabled mmW ARoF transmission of directly modulated 64-QAM UF-OFDM signals," *Opt. Lett.*, vol. 45, no. 18, p. 5246, 2020.
[3] C. Browning *et al.*, "Phase noise robust optical heterodyne system for reduced complexity millimetre-wave analog radio-over-fibre," in *Proc. ECOC*, 2019, pp. 1–3.
[4] P. D. Lakshmijayasimha *et al.*, "Tunable mm-wave A-RoF transmission scheme employing an optical frequency comb and dual-stage active demultiplexer," *J. Lightw. Technol.*, vol. 34, no. 24, pp. 7771–7780, Dec. 15, 2021, doi: 10.1109/JLT.2021.3098949.
[5] C. Yin *et al.*, "Microwave photonic frequency up-convertor with frequency doubling and compensation of chromatic-dispersion-induced power fading," *IEEE Photon. J.*, vol. 9, no. 3, pp. 1–7, Jun. 2017.
[6] H. Chen *et al.*, "Remote heterodyne millimetre-wave over fibre based OFDM-PON with master-to-slave injected dual-mode colorless FPLD pair," *Opt. Exp.*, vol. 23, no. 17, pp. 22691–22705, 2015.
[7] S. Fukushima, C. F. C. Silva, Y. Muramoto, and A. J. Seeds, "Optoelectronic millimeter-wave synthesis using an optical frequency comb generator, optically injection locked lasers, and a unitraveling-carrier photodiode," *J. Lightw. Technol.*, vol. 21, no. 12, pp. 3043–3051, Dec. 2003.
[8] P. D. Lakshmijayasimha, A. Kaszubowska-Anandarajah, E. P. Martin, M. N. Hammad, P. Landais, and P. M. Anandarajah, "Characterization of a multifunctional active demultiplexer for optical frequency combs," *Opt. Laser Technol.*, vol. 134, Feb. 2021, Art. no. 106637.
[9] T. Shao, M. Beltrán, R. Zhou, P. M. Anandarajah, R. Llorente, and L. P. Barry, "60 GHz radio over fiber system based on gain-switched laser," *J. Lightw. Technol.*, vol. 32, no. 20, pp. 3695–3703, Oct. 15, 2014.
[10] T. N. Huynh, L. Nguyen, and L. P. Barry, "Phase noise characterization of SGDBR lasers using phase modulation detection method with delayed self-heterodyne measurements," *J. Lightw. Technol.*, vol. 31, no. 8, pp. 1300–1308, Apr. 15, 2013.