5G Millimeter-Wave Analog RoF System employing Optical Injection Locking and Direct Modulation of DFB Laser

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Abstract: We demonstrate the successful generation of 28.2 and 35.3 GHz mm-wave signals through optical injection locking and direct modulation of a DFB laser. The low phase noise mm-wave signal generated supports 5G compatible OFDM signals.

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1. Introduction

Wireless signal transmission in the 24.6 GHz to 52.4 GHz millimeter-wave (mm-wave) frequency band will play an important role in 5th and 6th generation (5/6G) wireless communication systems to achieve higher data rates [1]. Optical heterodyning, wherein two optical carriers with a desired mm-wave frequency difference beat on a high-speed photodetector (PD), provides a promising solution for the generation of such mm-wave and higher frequency Terahertz carriers [2, 3]. A compatible analog radio-over-fiber (A-RoF) fronthaul link, in which the wireless data signal is modulated on one of the optical carriers at a lower intermediate frequency (IF), can be used to distribute the signals from the central office (CO) to the antenna remote radio head (RRH) site [4]. The frequency offset (FO) and phase noise (PN) of the mm-wave signal due to the beating of the uncorrelated optical carriers limit the performance of such optical heterodyne A-RoF system – especially for the 5G multi-carrier orthogonal frequency division multiplexed (OFDM) signals [3]. Therefore, it is essential to ensure that the beating optical carriers have correlated frequency and phase fluctuations, or alternatively, to successfully mitigate these effects through advanced system implementations.

Techniques such as the use of an optical frequency comb (OFC) source [3], optical phase-locked loop (OPLL) [5], and optical injection locking (OIL) [6] are generally used for correlating the frequency and phase fluctuations of the beating optical carriers. The OFC-based optical heterodyne A-RoF system generally requires the use of amplification stages and additional filtering to select the required tones [3], while the OPLL will require feedback from the PD output with an additional mm-wave mixing stage [5]. In optical injection locking based mm-wave systems [6, 7], highly correlated OFC tones are generated initially through a combination of low linewidth master laser with either an external modulator [6] or gain-switched laser [7]. These correlated tones are then injected into two independent slave lasers, with the desired mm-wave frequency separation, in order to correlate their frequency and phase fluctuations. Such architectures are successful in generating low PN mm-wave carriers, but their relative complexity is increased through the requirement of correlated OFC generation and a data modulation stage with an external modulator. Considering the potential wide-scale deployment of 5G mm-wave equipped antenna sites, it is necessary to reduce the complexity of such hybrid optical/mm-wave architectures while maintaining the low PN mm-wave generation properties required for the successful transmission of the 5G compatible subcarrier spacing OFDM signals.

In this work, we demonstrate a mm-wave optical heterodyne A-RoF system based on the optical injection locking (OIL) and direct modulation (DM) of a laser. A distributed feedback (DFB) laser is simultaneously modulated with a 5G compatible IF data signal and RF sinusoidal signal with a frequency close to the relaxation oscillation of the laser. The generated harmonics of the RF signal are injected into another DFB laser, at the RRH site, and the combined signal results in a low PN mm-wave signal generation after detection, at frequencies well above the modulation bandwidth of the DFB laser. We demonstrate the successful generation of OFDM signals at 28.2 GHz and 35.1 GHz frequencies with performance below the forward error correction (FEC) limit after transmission over 10 km of single-mode fiber (SMF). A similar configuration is demonstrated in [7], where a master injected laser is gain-switched to generate an OFC source and its output tones were injected in two slave lasers. Here, we also modulated the laser with a sinusoidal signal, but rather than using high power RF signal to generate the OFC, we exploit the nonlinear modulation response of the laser to our advantage – resulting in power-efficient implementation. The simultaneous modulation of the IF data signal eliminates the need of an additional laser compared to previous demonstration in [7].

2. Experimental Setup

The schematic of the optical heterodyne A-RoF system based on the OIL and DM of the DFB laser is shown in Fig. 1 with figurative spectra along the transmission path. A DFB laser with a relaxation oscillation peak of ~12.7 GHz was modulated simultaneously with a 5G compatible IF signal and 12.7 GHz RF sinusoidal signal (~15 dBm power) at the CO as shown in Fig. 1. The RF signal modulation in the nonlinear region results in the generation of harmonic

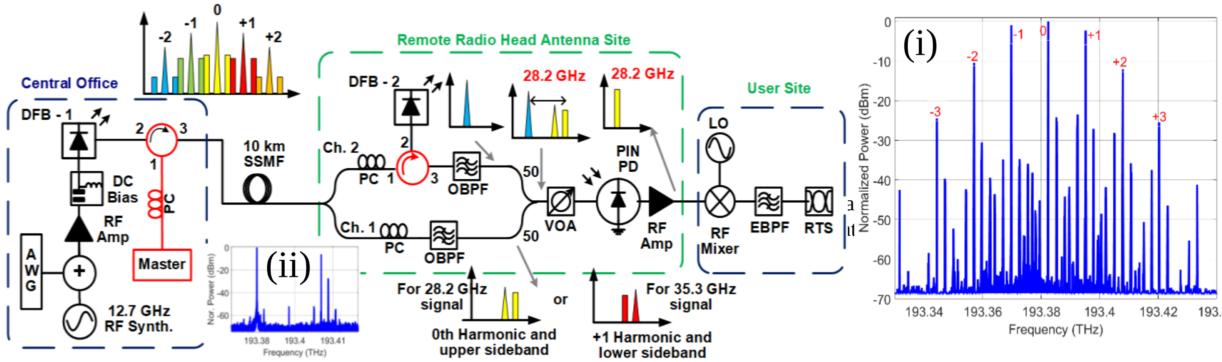

Fig. 1 Optical heterodyne mm-wave transmission system setup employing OIL and direct modulation of DFB lasers with insets (i) showing the optical spectrum at the output of DFB laser 1 at CO, and (ii) showing the optical spectrum at the input of photodetector.

components as seen from the optical spectra of Fig. 1(i). The first-order modulation components (+1 and -1), at 12.7 GHz, have approximately the same power as the main carrier, while the second and third-order harmonics, at 25.4 GHz and 38.1 GHz, are approximately 10 dB and 25 lower than the main carrier, respectively. The power in the harmonic components depends on the depth of modulation and the nonlinearity of the laser response. 195 MHz BW 5G compatible OFDM signals with variable subcarrier spacing were generated and frequency converted to the 2.8 GHz intermediate frequency in Matlab. The IF signal samples were loaded into the arbitrary waveform generator (AWG) at the transmitter and the generated signal was combined with the RF sinusoidal signal before laser modulation. The direct modulation of the IF 5G data signal will generate a double-sideband signal around the main carrier and all of the harmonics. The second-order harmonics of the data signals will be also generated depending on the depth of modulation. A low linewidth master laser was injected into this DFB laser in order to stabilize the frequency and phase fluctuations. The laser output was transmitted from CO to the RRH site through 10 km SMF.

At the antenna RRH side, the received signal was split into two channels – Ch.1 for filtering the IF data signal sideband and associated modulated carrier and Ch. 2 to lock a free-running slave DFB laser 2 to the second harmonic (-2) of the RF carrier as shown in Fig. 1. The locking of the DFB laser 2 by the second harmonic tone (-2) increases the optical power in this tone and results in an mm-wave signal generation with sufficient signal-to-noise ratio, after beating on a PD, to successfully demodulated the signal. Optical filtering is required in Ch. 2 to filter out additional signal components passing through the slave DFB laser 2 after injection. The filtered IF data signal sideband and associated carrier is combined with the amplified second harmonic carrier and the combined signal beats on the PD to generate the mm-wave signal. In the first case, the main carrier (0 harmonic) and associated data signals upper sideband is combined with amplified second harmonic (-2 harmonic) carrier to generate a 5G mm-wave signal at 28.2 GHz, while in the second case first harmonic carrier on the upper side (+1 harmonic) and associated data signals lower sideband are filtered and combined with amplified second harmonic (-2) carrier to generate a 5G mm-wave signal at 35.3 GHz frequency as shown by the figurative spectra in Fig. 1. This mm-wave data was captured using a real-time oscilloscope (RTS) after mixing it back to an IF stage with an external local oscillator (LO). Offline processing including re-sampling, channel equalization, bit error ratio (BER), and EVM calculations were performed using Matlab. The system's capabilities were investigated for the transmission of low subcarrier spacing multi-carrier signals by transmitting the OFDM signals with subcarrier spacing values of 2 MHz, 1 MHz, 500 kHz, 250 kHz, 125 kHz, and 62.5 kHz for both generated mm-wave frequencies. To keep the OFDM signal bandwidth constant, the IFFT size and number of data subcarriers were changed by a factor of two with respect to the previous subcarrier spacing signal.

3. Results

Initially, two different mm-wave carriers at 25.4 GHz and 38.1 GHz frequencies were generated with the system described above. For the generation of the 25.4 GHz carrier, the main carrier (0 harmonic - filtered in Ch. 1) and -2 harmonic (from injected slave DFB laser 2 in Ch. 2) were combined for heterodyne detection on the PD. For 38.1 GHz mm-wave carrier generation, the +1 RF signal harmonic (from Ch. 1) and -2 harmonic (from Ch. 2) were combined and beat on the high-speed PD. The PN of the generated carriers was measured using a spectrum analyzer and is shown in Fig. 2(i). Results show that both the generated carriers have a PN below -80 dBc/Hz at 1 kHz away from the carrier. The PN of the 25.4 GHz carrier reduces further to -115 dBc/Hz at 10 MHz, but that of the 38.1 GHz carrier reduces to -95 dBc/Hz only. This might be due to the use of the +1 harmonic modulated carrier, for beating, which is further away from the master laser than the main 0 order carrier used for 25.4 GHz carrier generation. Nevertheless, in both cases, the phase noise is low enough to produce a mm-wave signal with sufficient purity and no frequency fluctuations allowing performances below the FEC level to be achieved. The PN of the beat signal is observed to be the same for the case of back-to-back and 10 km fiber transmission, at both frequencies.

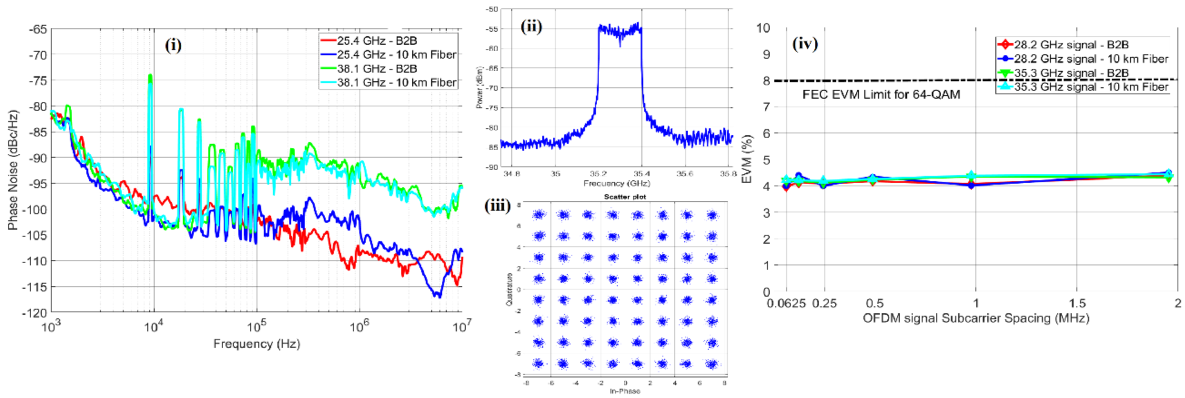

Fig. 2: (i) Phase noise of the generated 25.4 and 38.1 GHz mm-wave carrier the first set and (ii) RF spectrum of the generated 35.3 GHz mm-wave signal, (iii) constellation of the 28.2 GHz mm-wave signal after frequency down conversion and demodulation, (iv) EVM versus subcarrier baud rate performance for OFDM signal over mm-wave A-RoF system employing OIL and direct modulation of DFB lasers.

In order to observe the systems performance, we modulated a 2.8 GHz IF OFDM data signal (with ~2 MHz subcarrier spacing) along with RF 12.7 GHz carrier on the first DFB laser 1. This allowed us to generate the mm-wave signal at 28.2 and 35.3 GHz frequencies as described in the above section. The RF spectrum of the generated signal at 35.3 GHz is shown in the inset (ii) of Fig. 2, while the constellation of the frequency down-conversion and demodulation signal is shown in Fig. 2(iii). This constellation, with an EVM of ~4%, indicates a successful mm-wave signal generation and transmission over 10 km optical heterodyne A-RoF link resulting in 64-QAM subcarrier modulated OFDM data transmission at the rate of ~1.17 Gb/s. Finally, the outlined systems performance was analyzed for the transmission of variable subcarrier spacing OFDM signals. The obtained results, shown in Fig. 2(iv), indicates that for the implemented system, performance is almost the same at all the subcarrier spacing from 2 MHz to 62.5 kHz, for both the frequencies – showing its capabilities to successfully transmit the 5G NR compatible subcarrier spacing (60 kHz and higher) OFDM signals. Even though the phase noise of the 38.1 GHz carrier is slightly worse than the 25.4 GHz carrier (as seen in Fig. 2(i)), it is sufficiently low to successfully demodulated the OFDM signals. The result shows no performance penalty after 10 km fiber transmission – similar to the PN findings. The obtained EVMs are well below the 8% FEC limit of 64-QAM data modulated signal.

The mm-wave system described here results in an excellent performance compared to our previous demonstrations using a mode-locked laser OFC source [8], while completely negating the requirement for optical amplification stages. The simultaneous direct modulation of the IF data and RF sinusoidal signal allows external modulation-free system implementation. Moving the remote injection locking and data filtering stage (which has potential be integrated on a single chip) to the CO can further reduce the complexity of the RRH antenna site. The low phase noise and constant performance over a wide range of OFDM subcarrier spacing highlight the potential of the outlined OIL and DM of DFB laser-based optical heterodyne A-RoF system for the mm-wave 5G and beyond 5G wireless systems.

4. Conclusion

A simple and impairment-free optical heterodyne A-RoF link capable of generating low phase noise mm-wave carriers can be a promising cost-efficient solution for the 5G and beyond 5G wireless systems. The system presented here based on the optical injection locking and direct modulation of the DFB laser demonstrates the generation and transmission of 28.2 and 35.3 GHz OFDM signals. The low phase noise of the generated carriers from the heterodyne system supports the transmission of 5G compatible OFDM signals with subcarrier spacing well down to 62.5 kHz – showing its potential for the deployment in the 5G mm-wave wireless systems. The possibility of photonic integration of most of the components can further reduce the complexity and cost of this system.

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