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24 GHz UWB-over-Fibre System for Simultaneous Vehicular Radar and Communications

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Abstract: An ultra-wideband (UWB)-over-fibre system in the 24 GHz band suitable for simultaneous short-range radar and vehicle-to-vehicle and vehicle-to-infrastructure communications is proposed. A photonic technique to generate millimetre-wave impulse-radio UWB (IR-UWB) signals is also proposed and demonstrated in a proof-of-concept experiment. An IR-UWB signal comprising monocycles with 5 GHz bandwidth and bearing a data stream at 622 Mbit/s bitrate is generated at 19 GHz employing frequency up-conversion in a Mach-Zehnder electro-optic modulator and further balanced photoreception for monocycle shaping. Experimental electrical down-conversion of the RF monocycles is also performed achieving a pulse quality with a BER of $5.4 \cdot 10^{-6}$.

Keywords: Microwave photonics, Ultra-wideband (UWB), impulse-radio UWB, optical frequency conversion, UWB communications, UWB-over-fibre, Vehicular radar.

1. Introduction

Ultra-wideband (UWB) is an attractive wireless technology for low-cost short-range high-bitrate communications. The major advantages of UWB include large bandwidth (BW), low power spectral density (PSD), and low-cost equipment. UWB has been defined in the United States by the Federal Communications Commission (FCC) as a radio modulation technique with a 10 dB BW of at least 500 MHz or 20% fractional BW. The FCC has regulated UWB in the band from 3.1 to 10.6 GHz for indoor communications and in the band from 22 to 29 GHz for vehicular radar applications [1]. The generic Harmonized European Standard for UWB communications [2] has defined a 23 dB BW higher than 50 MHz and a frequency range from 6 to 8.5 GHz, and the 3.1 to 4.8 GHz range provided detect-and-avoid (DAA) mitigation techniques are employed. DAA specifications for UWB in 3.1 to 4.8 GHz as well as in 8.5 to 9 GHz are included in [3]. Moreover, UWB has been regulated in Europe for 24 GHz vehicular short-range radar (SRR) systems (short-term) for road safety [4]. The maximum radiated PSD is -41.3 dBm/MHz in all the previous cases to minimize the interference on licensed or un-licensed wireless services [5]. European standardization also includes other applications such as 79 GHz SRR (long-term), ground- and wall-probing radar, tank level probing radar, sensors and precision location within buildings. Furthermore, 60 GHz UWB is emerging as a viable approach for ultra-high rate wireless communications [6]. The 60 GHz band is attractive due to the large unlicensed frequency range available, almost worldwide [7].

Due to the extremely low emission power regulated, current UWB systems can operate with a distance limited to 10 m. UWB-over-fibre technology has received great interest to extend the UWB range exploiting the advantages of optical fibres [8]. Two main UWB implementations are currently available: Impulse-radio UWB (IR-UWB) and OFDM-based UWB (OFDM-UWB) following the ECMA-368 standard [9]. IR-UWB employs short radio pulses, typically in the picoseconds range, and is able to provide communications, localization and ranging simultaneously. In addition, IR-UWB enables adjusting the desired BW. This is not possible with OFDM-UWB, in which the minimum BW is 500 MHz. Furthermore, compared to OFDM-UWB, IR-UWB is not channelized, thus simplifying the overall system management.

UWB is experiencing an important interest in vehicular short-range applications, involving outdoor communications, also known as car-2-car (C2C) and car-2-infraestructure (C2I) [10], and radar sensors [11]. 24 GHz IR-UWB systems are an interesting solution for high-resolution SRR, which aims target detection within a maximum range of 10 m [12].

The simultaneous use of 24 GHz IR-UWB signals for vehicular SRR ranging and communications is proposed in this paper. The RF IR-UWB signal is optically generated and distributed through fibre as in an in-car UWB-over-fibre installation, targeting to provide car-safety applications. Reported work proposed photonic generation of IR-UWB signals frequency up-converted to the 24 GHz band [13-17]. The work herein reported proposes and demonstrates a photonic generation technique capable of generating IR-UWB signals in the 24 GHz band simultaneously bearing a data stream at 622 Mbit/s bitrate in a proof-of-concept experiment. This approach exhibits several advantages: (i) Reduced complexity; (ii) It employs a low-jitter pulsed laser source, which allows implementing a wavelength division multiplexing (WDM) radio-over-fibre system and improving the quality of the UWB pulses. Nevertheless, electrical Gaussian sources could be employed in this technique; (iii) It is suitable for providing simultaneous high-speed communications and high-resolution SRR ranging. In this work, zeros are introduced in the data sequence, with ones and zeros equally frequent thus emulating a random bit sequence. (iv) It is frequency-flexible, i.e. the technique can inherently generate signals at higher frequencies, e.g. in the 60 GHz band, provided adequate components are employed.

This paper is divided in four sections: In Section 2, the proposed 24 GHz UWB-over-fibre system and its application to simultaneous vehicular SRR and communications is described. The experimental photonic generation of IR-UWB signals at 19 GHz and further electrical detection is reported in Section 3. Finally, the conclusions are given in Section 4.

2. 24 GHz UWB-over-Fibre for Simultaneous Vehicular Radar and Communications

In the proposed in-car 24 GHz UWB-over-fibre system, the RF IR-UWB signal is optically generated and distributed through standard single-mode fibre (SSMF) interconnecting a large number of UWB transceivers along a given in-car infrastructure. The same RF IR-UWB signal supports vehicular SRR and C2C/C2I communications applications to provide traffic safety. The huge fibre BW enables large count low-cost and small UWB transceivers arranged in arrays employing dense WDM (1 channel/transceiver). The large count of UWB transceivers enables high resolution positioning estimation in vehicular radar and permits to develop MIMO processing thus enabling directional C2C communications.

The advantages of IR-UWB for the proposed application are: 1) High-accuracy SRR; 2) Simultaneous vehicular SRR and communications on the same RF signal; 3) Easy data encryption. Figure 1 depicts the proposed UWB-over-fibre system together with the car-safety applications. The block marked “Processing unit” in Figure 1 comprises the photonic signal generation and detection. The IR-UWB modulated on a set of optical carriers (WDM

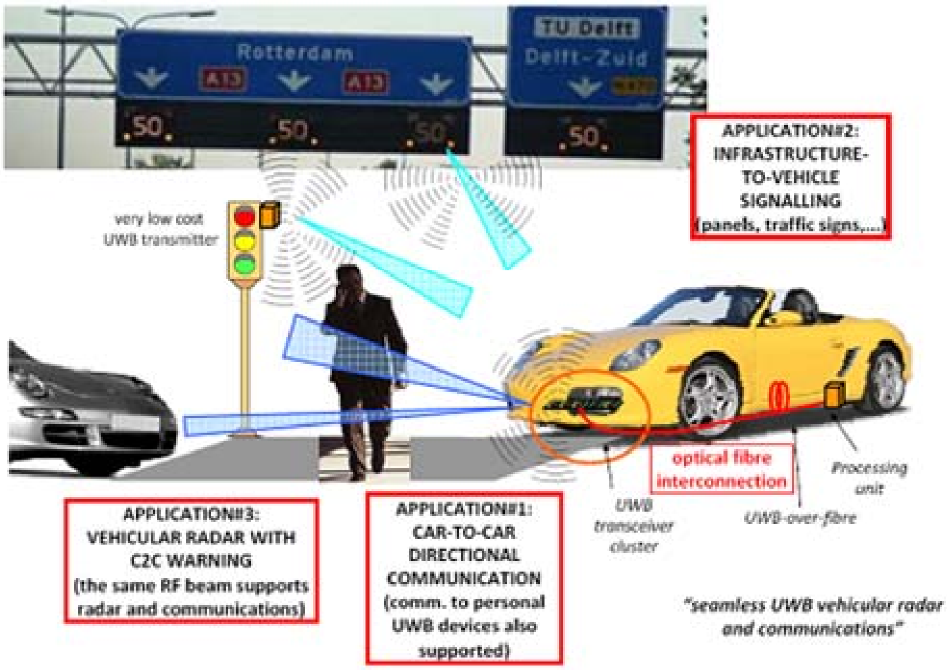

Figure 1: 24 GHz IR UWB over fibre for car-safety applications approach.

channels) is distributed over SSMF to the UWB transceivers. In the UWB transceiver array, the data signal is photodetected resulting in an electrical IR-UWB signal in the 24 GHz band, which is further amplified and filtered to be radiated.

The car-safety applications are summarized next:

1. Vehicular radar and simultaneous communications. Some examples are: Collision detection and warning, lane change warning, rear closing vehicle warning, pedestrian detection, cross traffic warning, side impact pre-warning, air bag pre-arming.
2. C2I signalling. The IR-UWB signal is employed to repeatedly transmit, for example exceptional road conditions warning.
3. C2C directional communications. For example, in case of an emergency braking, a warning signal is sent only in the direction of potential colliders.

In the next section, an experimental demonstration of the proposed system for one WDM channel without fibre transmission is reported. RF IR-UWB monocycles are optically generated and further detected with conventional electrical down-conversion.

3. Photonic Generation of Millimetre-Wave Impulse-Radio UWB Signals

A photonic technique for RF IR-UWB signal generation employing frequency up-conversion is demonstrated in this section. The technique generates IR-UWB monocycles with 5 GHz BW at 622 Mbit/s repetition rate up-converted to 19 GHz. The signal in the 24 GHz band can be generated by the same technique provided adequate electrical devices are employed. The generation process comprises three stages: First, the generation of optical Gaussian pulsed data. Second, the frequency up-conversion employing a Mach-Zehnder electro-optic modulator (MZ-EOM). Third, the monocycle shaping to an adequate UWB spectral envelope employing balanced photodetection.

Figure 2 shows the schematic of the RF IR-UWB monocycle photonic generator. A bit pattern generator (BPG) is used to generate a non-return-to-zero (NRZ) data pulsed sequence (01010101) with a pulsewidth (FWHM) of 40 ps and a repetition rate of 622 Mbit/s. An actively mode-locked laser (MLL) is employed to generate an optical pulse train with 2 ps FWHM at 1554 nm and timing jitter lower than 1 ps, which is intensity modulated in a MZ-EOM with the data (MZ-EOM #1 in Figure 2). The data optical pulses are time-stretched in 10 km of SSMF to adjust the BW of the generated monocycles. Then, the stretched data pulses are amplified with an Erbium-doped fiber amplifier (EDFA), which is required to reach the photodetector sensitivity, and it is configured to adjust an adequate PSD at point (1) in Figure 2. A local oscillator (LO) at a frequency of 19 GHz with 15 dBm power is modulated on the data pulses in a MZ-EOM (V_π= 3.7 V) (MZ-EOM #2 in Figure 2) biased to work as a conventional double-sideband modulator. The choice of 19 GHz as a RF carrier frequency is determined by the available electrical amplifier (eAmp #2 in Figure 2) which is operational in the band from 17 to 22 GHz. Subsequently, the modulated RF signal is equally split into two paths to be applied to the inputs of a balanced photoreceiver with limiting transimpedance amplifier (TIA) (Teleoptix, DualPIN-DTLIA Rx) [18]. A variable optical delay line (ODL) is used to adjust the relative delay between the two inputs and a variable optical attenuator (VOA) is used to compensate the path loss difference. At the photoreceiver output, IR-UWB monocycles up-converted to the LO frequency are obtained. Next, this RF IR-UWB signal has to be filtered to remove the unwanted frequencies before being radiated.

Figure 3(a) shows the RF spectrum of the UWB monocycles at 19 GHz measured at point (1) in Figure 2. This spectrum exhibits a double-sideband BW of 5 GHz and a maximum PSD close to the -41.3 dBm/MHz limit. A dynamic range higher than 20 dB is achieved. In the experiment, the electrical filtering of the generated UWB signal is performed by the amplifier eAmp #2 in Figure 2, by which a unique sideband cannot be filtered. Nevertheless, the residual carrier at 19 GHz does not limit the maximum PSD [14]. The transmission of the two spectral sidebands can increase the receiver sensitivity but at expense of the reduced spectral efficiency.

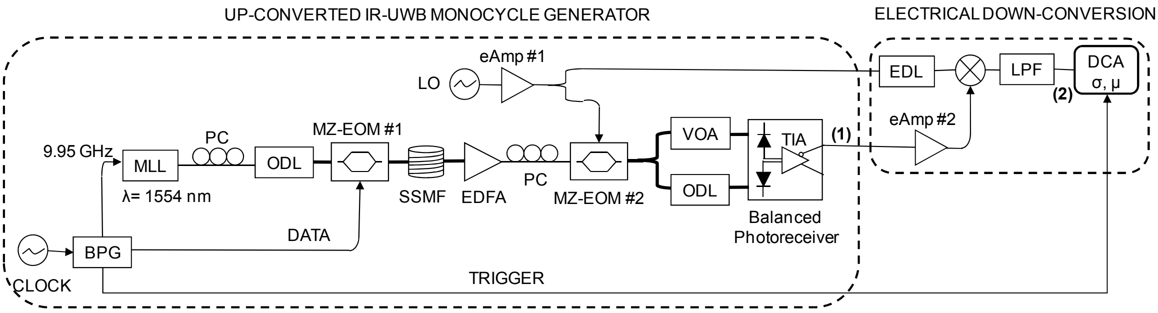

Figure 2: Experimental setup for 24 GHz IR-UWB signal generation and detection. PC: Polarization Controller.

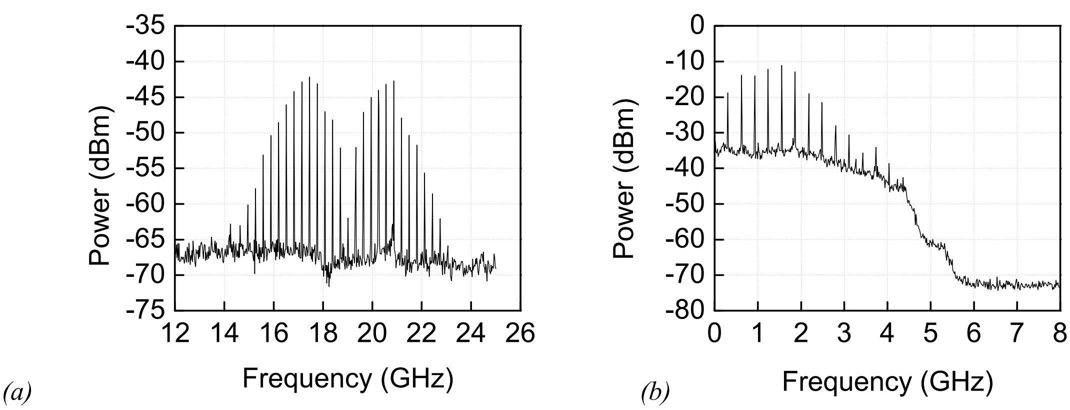

Figure 3: (a) RF spectrum of the IR-UWB RF monocycles at point (1) in Figure 2 (Resolution BW=1 MHz). (b) RF spectrum of the down-converted monocycles at point (2) in Figure 2 (Resolution BW=1 MHz).

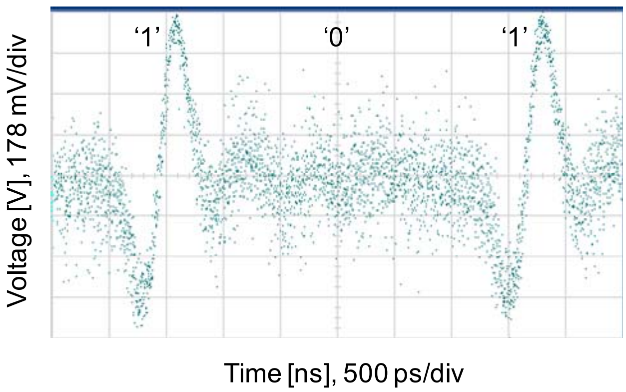

Figure 4: Down-converted monocycles at point (2) in Figure 2.

To validate the technique for RF IR-UWB generation, the electrical demodulation of the IR-UWB signal at 19 GHz previously generated is performed employing an electrical mixer (6-18 GHz LO/RF, DC-3 GHz IF), as shown in Figure 2. The LO with 15 dBm power is mixed with the RF IR-UWB signal at point (1) in Figure 2 amplified to a maximum PSD of -10 dBm. An electrical delay line (EDL) is employed in the LO to fine tune the phase of the LO for accurate down-conversion. Afterwards, the signal frequency down-converted to baseband is low-pass filtered (LPF) (3.3 GHz BW) and measured by a digital communications analyzer (DCA) (HP83481A, 12.4 GHz BW). Figure 3(b) shows the RF spectrum of the down-converted pulses and Figure 4 shows these pulses in the time domain, measured at point (2) in Figure 2. To evaluate the quality of the received pulses, the signal-to-noise ratio (Q-factor) is evaluated from the measurements. The histogram of the two symbols ('0' and '1') is measured and employing the power level, the standard deviation (σ) and the mean (μ) of the two symbols, a Q-factor of 4.4 is obtained corresponding to a calculated bit error rate (BER) of $5.4{\cdot}10^{-6}$, as given by $BER = 0.5 \cdot erfc\left(Q/\sqrt{2}\right)$ assuming Gaussian noise. The quality achieved in the experiment is enough for wireless transmission incorporating forward error correction (FEC) codes so that the feasibility of the proposed technique is demonstrated.

In order to improve the performance, the noise level in the system has to be reduced. Also, the mixer causes spectral deterioration of the received UWB signal impacting the tradeoff between quality and spectral efficiency.

4. Conclusions

An UWB-over-fibre system in the 24 GHz band is proposed for simultaneous vehicular SRR and communications. The experimental work demonstrates the photonic generation of the RF IR-UWB signal at 19 GHz with 5 GHz double-sideband BW bearing data at 625 Mbit/s. The up-converted signal is further detected by electrical down-conversion achieving good quality.

Compared to previous techniques, the proposed generation approach achieves higher spectral efficiency which can be better if single-sideband filtering is performed. Moreover, the quality of the received pulses is quantified, and a data sequence including zeros is employed, which reduces the PSD so that higher power is required in the system to reach the -41.3 dBm/MHz limit.

Further research is on-going on improving the system performance and including fibre transmission. Optical detection is also under study as it is well suited for in-vehicle networks, as external interference from the car engine is strongly reduced.

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