PHOTONICS IN WIRELESS TRANSCEIVERS

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ABSTRACT

During the last few years, the cross-fertilization between photonics and radio systems has been helping to overcome some major limitations of the classical radio technologies, setting new paradigms, and promising improved performance and new applications with strong benefits for public communications and safety. In particular, photonics-based wireless systems, albeit still at research level, are moving toward a new generation of multifunctional systems able to manage the wireless communication with several different frequencies and protocols, even simultaneously while also realizing surveillance operations. Photonics matches the new requirements of flexibility for software-defined architectures, thanks to its ultra-wide bandwidths and ease of tunability, and guarantees low footprint and weight, thanks to integrated photonic technologies. Moreover, photonics also allows increased resolution and sensitivity by means of the inherent low phase noise of lasers.

In this paper we review, from a technical point of view, the impact that the demonstrated photonics have in wireless systems, and we consider the related spin-offs for other applications relevant to society. We also describe the first demonstrator of photonics-based multifunctional transceiver presented in Nature Journal (Ghelfi, et al., 2014), that sets a breakthrough innovation in the scientific panorama.

Keywords: *Microwave Photonics, Mode Locking Laser, Wireless Communications, Radar.*

1. INTRODUCTION

Today s wireless communication systems need specific hardware working at specific radio frequencies, with characteristic signal waveforms and bandwidths, requiring dedicated apparatus for each single application. Moreover, next personal communication will need to exploit new frequency bands as the unlicensed millimeter waveband around 60 GHz. The current electronic devices present increasing limitations and poor performance as the frequency gets higher. Similarly, next surveillance systems will require higher carrier frequency for smaller antennas, broadened bandwidth for increased resolution, and software-defined signal generation and detection (the so-called software-defined radio approach, SDR) for flexibility in variable environments (Skolnik, 1980; Haykin, 2006). Therefore, in most of the future transceivers for wireless applications (either communications or surveillance) it will be necessary to generate and receive very stable high-frequencies and wide-band RF signals by means of reliable transmitters/receivers that also respect constraints in size, weight and power consumption (SWaP). Besides this, flexibility and reconfigurability will be another fundamental requirement in tomorrow s systems. For example, in the cognitive radio paradigm, an intelligent radio technology will exploit wide-band receivers in order to automatically detect available channels in a wireless spectrum and constantly monitor the link performance. By adaptively changing the transmission parameters, this technology paradigm will allow to enhance the performance of the whole wireless communications. In the field of radar systems, a new concept of multifunctional radar will be desirable in order to merge in the same apparatus different applications for meteorology, environment monitoring, target detection and communication. In particular, the integration of surveillance and communication functions in a single dual-use system will allow to fully exploit the potentials of its efficiency and flexibility. This functional integration will also enable a reduction of cost and power consumption through the sharing of the same hardware among different functions. Finally, another example concerns the aerospace scenario where the number of applications that rely on satellite navigation systems has strongly increased in the last two decades. Future navigation systems will require even more precise and reliable transceivers in order to offer safety-of-life services and multiple functionalities for reducing the satellite payloads and maximize the satellite life. All of these strategic applications require reduced size, weight and power consumption to enhance their efficiency and effectiveness.

Today s microwave components suffer limited bandwidth, poor flexibility, and high noise at increasing carrier frequencies (Scheer, 1993; Walden, 2008). In conventional electronic RF transceivers, the major limitations comes from the reduced dynamic range due to multiple-stage down-converting mixers, the limited port-to-port isolation at the mixer, and the excessive size, weight, and power requirements of the front-ends. Such front-ends are known to be noisy and suffer from electromagnetic interferences, causing degradation of the sensitivity and of the dynamic range of the final system. These deficiencies are magnified as wider bandwidth systems are developed. Figure-1

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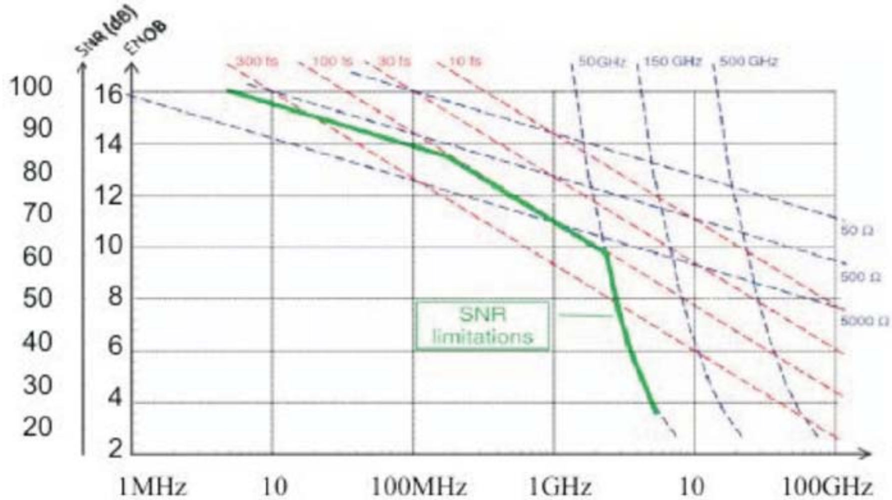

Source: *Piqueras, et al., 2011*

Figure-1: SNR (or ENOB) Limitations of ADCs as a Function of the Input Frequency
The graph reports the main limiting causes for SNR: (i) thermal, shot, and flicker noise contributions, affecting SNR at lower frequencies; (ii) jitter of the sampling clock, affecting the performance at higher frequencies; (iii) ambiguity (or transition frequency), main limitation at highest frequencies. The highlighted green line shows the SNR limits for an ADC with 1kΩ input thermal resistor, jitter of 100fs, and 50GHz of transition frequency.

shows the limits of the signal-to-noise ratio (SNR), or of the effective number of bits (ENOB), for electronic analog-to-digital converters (ADCs) due to different noise contributions, as a function of the input analog bandwidth (Piqueras, et al., 2011). As can be seen, an ADC accepting signal frequencies above 10 GHz with decent SNR (>50 dB) need to show extremely low sampling jitter and very fast switching devices that are hard to be achieved with the current electronic technologies.

On the contrary, photonics has proved high precision and ultra-wide bandwidth (Capmany and Novak, 2007; Yao, 2009), allowing the generation of extremely stable multiple radio-frequency (RF) signals with arbitrary waveforms up to the millimeter waves (Khan, et al., 2010; Ghelfi, et al., 2012), and their detection and precise direct digitization (i.e., without noisy RF down-conversions) (Khilo, et al., 2012; Laghezza, et al., 2013). Up to now, the photonics-based generation and detection of RF signals have been studied only separately and never verified in a radar system. We recently presented the development and the characterization of the first fully photonics-based RF transceiver, which is now being tested in a radar application (Ghelfi, et al., 2014). The proposed architecture exploits a single pulsed laser for both generating and detecting the tunable RF signals, avoiding RF up-/down-conversions and guaranteeing software-defined approach, multiple functionalities, and high resolution, with performance exceeding the state-of-the-art electronics at carrier frequencies above 10 GHz. The foreseen implementation of the proposed architecture by means of integrated-photonics circuits will further increase its potentials, leading to compact and flexible systems suitable for the most requiring future wireless systems.

2. THE PHOTONICS-BASED RF TRANSMITTER AND RECEIVER

In the past few years simple architectures for the photonic generation of RF signals have been envisioned based on the heterodyning of two independent lasers (Goldberg, et al., 1983; Sun, et al., 2006), but these implementations do not allow for a stable RF generation, making the obtained signal not useful for future requiring systems. In order to improve RF stability, phase locking of the beating lasers is necessary, and this usually requires more complex and cumbersome set-ups (Goldberg, et al., 1992). A relatively simple technique for generating phase locked laser lines is the mode locking of lasers (Serafino, et al., 2010; Yilmaz, et al., 2002): the intrinsic phase-locking condition of the mode-locked laser (MLL) ensures an extremely low phase noise of the generated RF signal. Moreover, the possibility of selecting laser modes with variable wavelength detuning allows the flexible production of RF carriers with tunable frequency, potentially generating any multiple frequency of the MLL repetition rate. Moreover, Serafino, et al., (2010) measured and analyzed the phase noise of the obtained RF carriers, demonstrating that they can be significantly less noisy than the signals generated by the state-of-the-art RF synthesizer.

To implement advanced communication functionalities, the photonics-generated carriers must be modulated into amplitude and/or phase-coded signals via electronics methods, which would require frequency-specific RF components that become more expensive at increasing frequency. An alternative modulation and coding approach based on photonics could instead allow broad RF bandwidth without restrictions on the carrier frequency selection. Few example of this approach have been proposed so far, based on wavelength-to-time conversion (Lin, et al., 2005), on microwave photonic filters (Chi and Yao, 2007), or on the heterodyning of phase modulated continuous-wave lasers (Li, et al., 2011). We have proposed few schemes that exploit the same approach as for the carrier generation, based on the use of a MLL. In the schemes, the modulated RF signal is generated by heterodyning two modes from a MLL, one of which is modulated by the low-pass modulation signal. In this approach, the modulation signal can be generated by a digital synthesizer with narrow analog bandwidth, and directly up-converted by photonic techniques through the heterodyning. Typical Wi-Fi OFDM (orthogonal frequency-division multiplexing) signals and compressed radar pulses have been generated with these techniques, with carrier frequencies up to 40 Ghz. The schemes allow the photonic generation of arbitrary phase-modulated RF pulses with flexible carrier frequency, and phase stability suitable for coherent radar systems. By properly choosing the MLL repetition rate, frequency agility can be also implemented. The carriers can be generated simultaneously or alternately, or even changed continuously. The modulating signal can also be changed meanwhile, implementing a waveform diversity technique.

The receivers for SDR would need high speed ADCs with huge analog input bandwidth spanning over several tens of GHz, and with high spurious-free dynamic range (SFDR) as well as SNR. As described above, precise electronic ADCs show limited analog input bandwidth, since at high input frequency the aperture jitter of the sampling clock affects the accuracy of the digitized signal. Today s best electronic ADCs show an aperture jitter of hundreds femtoseconds with only few GHz of analog BW (Walden, 2008). Optical sampling can overcome the limitations faced by electronic ADCs (Khilo, et al., 2012), and in the last decade several photonics-assisted ADCs have been proposed, based on the electrical detection of modulated optical pulse trains with subsequent sample parallelization schemes. Most of these works resort to the concept of under-sampling to acquire RF signals with bandwidth up to few GHz but carrier frequency up to several tens of GHz. The use of narrow-pulse MLLs with very low temporal jitter guarantees a precise sampling time and a digitized signal with low jitter-limited noise floor. The high electro-optical bandwidth of the optical modulators can broaden the analog input bandwidth of photonic-assisted ADCs up to tens of GHz. Sample parallelization by time- or wavelength-interleaving schemes have been proposed to enlarge the instantaneous bandwidth (i.e., the maximum signal bandwidth) of the photonic ADCs by exploiting a MLL with high repetition rate and a set of parallel low-speed high-precision electronic converters. But the data interleaving can also produce spurious peaks due to the inequalities of the data arrays in the parallel channels, and to the non-idealities of the parallelizing method as time skew and crosstalk (Williamson, 2001). While wavelength-interleaving is most sensible to the time skew, time-interleaving suffers the inter-channels crosstalk due to the limited extinction ratio of the optical switching matrix. Digital post-processing techniques are usually applied to minimize the effect of such spurious components and to maximize the precision of the photonic ADC (Elbornsson, et al., 2005).

We have proposed the exploitation of the time-interleaving approach to avoid the time skew issues, and presented a photonic ADC based on a 4-fold time-interleaving with an extremely low sampling jitter where the limited extinction ratio of the optical switching matrix is compensated for by a real-time digital post-processing reducing the spurious tones (Laghezza, et al., 2013). The realized ADC has shown a state-of-the-art precision above 7 effective bits up to 40GHz with an instantaneous bandwidth of 200 MHZ. The scheme demonstrates to approach the theoretical limit imposed by the sampling jitter, and to be easily scalable to larger signal bandwidth with the current photonic technologies.

3. THE PHOTONICS-BASED RF TRANSCEIVER

The realization of an entire optics-based RF transceiver can therefore exploit a single MLL for both the transmitter and the receiver, thus optimizing the overall impact of the photonics-based approach in the total system cost. We have followed this approach to realize the first full photonics-based RF transceiver.

We have focused on the specific application to surveillance system. Under this assumption, the carrier frequency of the sampled signal must not coincide with an integer multiple of the sampling frequency, which is unfortunately the case if the RF signal is generated by the beating of two modes from the sampling laser. This constraint can be overcome exploiting the concept of shifting the frequency of one laser mode while maintaining the original phase stability of the MLL. The frequency shift can be realized modulating the mode with a RF oscillator with a small frequency and negligible phase noise compared to the MLL. This is usually the case if low-frequency crystal oscillators are used (Ghelfi, et al., 2011). Moreover, in coherent radars a reference signal is also necessary to detect the Doppler shift on the received echo, and in-phase/quadrature detection must be implemented. The scheme of principle of the realized photonics-based radar transceiver is reported in Figure-2.

The exploited MLL has a repetition rate of 400 MHz, and generates sub-ps pulses with a timing jitter lower than 10 fs (integrated for offset frequencies in the range (10 kHz 10 MHZ). The photonics-based RF generator has been tested producing signals with carriers up to 40 GHz (limited by the photodiode bandwidth) and excellent stability. Modulated RF signals have been also generated directly by using photonic techniques, with broad instantaneous bandwidth potentially ranging up to 200 MHz. The photonics-based ADC has been tested with input continuous-wave (CW) signals in the full range up to 40 GHz, generated by a state-of-the-art synthesizer. The system has reached a precision of 7.4 effective bits for input signal at 10 GHz, and 7 effective bits at 40 Ghz, performing significantly better than the reported electrical ADCs. Moreover, at 40 Ghz the system performance has been measured to be close to the theoretical limit posed by the aperture jitter of 10fs. The test results of the photonics-based transceiver are summarized in Table-1, compared with the performance of the state-of-the-art electronic radar transceivers (Richards, et al., 2010). The advantages of the photonic approach are evident in the extreme frequency flexibility over tens of GHz, in the arbitrary modulation capability, and in the precision of the digitization for any input frequency. These features will enable the SDR paradigm in future radars, as well as in the next generation of flexible wireless communication systems.

The photonics-based transceiver has been inserted in a radar demonstrator with the aim of running field trial

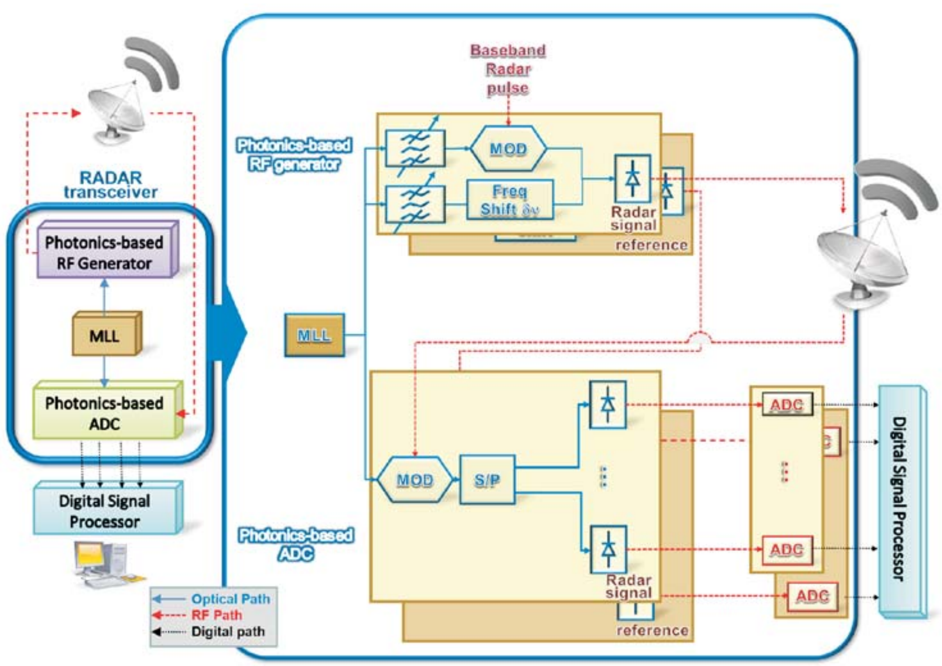

Figure-2: Scheme of Principle of the Photonics-based Transceiver in the Case of Application to Coherent Radars

Table-1: Performance of the Photonics-based Transceiver, Compared with the State-of-the-Art Electronic Transceiver

Parameter	Photonics-based transceiver	State of the art electronics transceiver
Transmitter		
Carrier frequency	Flexible direct generation up to 40GHz	Direct generation below 2GHz up-conversions above 2GHz
Signal jitter	<15fs integrated in [10kHz-10MHz]	Typical >20fs integrated in [10kHz-10MHz]
Signal-to-noise ratio (SNR)	>73dB/MHz	>80dB/MHz
Spurious-free dynamic range (SFDR)	>70dBc	>70dBc
Instantaneous bandwidth	200MHz, easily extendable with MLL at higher repetition rate	<2GHz
Receiver		
Input carrier frequency	up to 40GHz with direct RF undersampling	<2GHz down-conversions at higher frequencies
Instantaneous bandwidth	200MHz, easily extendable with MLL at higher repetition rate	<2GHz
Sampling jitter	<10fs integrated in [10kHz-10MHz]	Typical >100fs integrated in [10kHz-10MHz]
Spurious-free dynamic range (SFDR)	50dB	>70dB
Effective number of bits (ENOB)	>7 for carrier frequency up to 40GHz	<8 for carrier frequency <2GHz

measurements to set its effectiveness in a real application. To this extent, a RF front-end (RF circulator, switches, amplifiers, filters, and bistatic antenna) for a signal carrier at 9,900 MHz is going to be used. Figure-3 reports the results from the recent laboratory trial in a back-to-back configuration, i.e. without launching the radar pulses from the antenna. The system has been set to generate a frequency mismatch between the radar signal and the reference signal, in order to emulate a Doppler shift due to a moving target. Moreover, the radar signal is generated with a delay in order to emulate the distance of the target. Figure-3 (a) shows the calculated distance/velocity map when a target at 5.2 km moving at 83 km/h is detected by means of an unmodulated radar pulse with a duration of 1 μs and a repetition rate of 10 kHz. The zoom in the figure shows a resolution of 150 m in distance and 2 km/h in velocity. Figure-3 (b) reports the distance velocity map in the case of a target at about 9 km approaching at 30 km/h, when the radar is software-driven to generate an RF pulse modulated with a Barker code. As can be seen, the resolution in distance is strongly improved, down to 12 m. Figure-3 (c) and (d) report the distance profile in the case of unmodulated and modulated radar pulse, respectively. The increase in resolution is well evident. The demonstrator will be tested soon in a real environment.

4. COMMENTS AND CONCLUSIONS

The potential of photonics in wireless systems has been revisited, focusing on its spin-offs for applications relevant to society. The first demonstrator

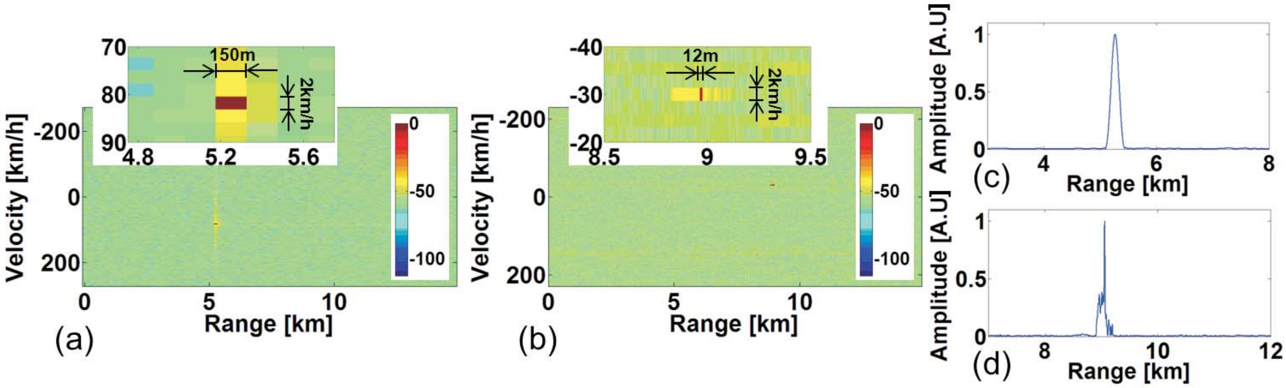

Figure-3: Results from the Back-to-Back Test of the Radar Demonstrator (a): Distance/velocity Map in Case of Unmodulated Radar Pulse. (b): Distance/velocity Map in Case of Radar Pulse Modulated with a Barker code. (c): Distance Profile of Case '(a)'. (d): Distance Profile of Case '(b)'

of photonics-based multifunctional transceiver presented in Nature Journal (Ghelfi, et al., 2014), has also been reported, that sets a breakthrough innovation in the scientific panorama. The characterization of the proposed photonics-based transceiver has highlighted the potentials of photonics to overcome the performance of electronics in terms of flexibility, signal quality, resolution at high frequency, and to enable the SDR and cognitive radio approaches. The proposed photonics-based transceiver has been implemented considering the specific application in a coherent radar system, and to this extent it is characterized by specific features as the frequency shift of the generated carrier and the coherent I/Q detection, which are not required in more generic applications. The radar demonstrator has proved the effectiveness and the expected precision of the photonic solution, which would be fundamental even in wireless communications applications. Nevertheless, an implementation based on dedicated integrated-photonics optical circuits (which is already under development) will fully enable the potentials of the photonic approach, leading to compact and flexible systems suitable for the most requiring applications. For example, photonics will allow the implementation of multifunction systems simultaneously realizing surveillance and communications, also including the signal beamforming in phased-array antennas, and the antenna remotization (Ghelfi, et al., 2013). The photonics-based implementation of additional functions will also bring the positive consequence of further reducing the impact of photonics in terms of cost on the entire system.

From the societal point of view, the availability of multifunction, smart communication/surveillance systems can improve the quality of our lives by flexibly adapting to different protocols, thus reducing the infrastructure costs for wirerless communications, and at the same time by gathering more data with increased precision by means of smaller and greener systems which can be networked together. The larger amount of information can then be used to improve the protection of people from any kind of threat, from homeland security to weather and environment monitoring.

The proposed photonics-based transceiver architecture is therefore expected to open new frontiers in the wireless systems, enabling future smart multifunction communication/surveillance systems that can improve the quality of our lives.

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