

Fully photonics-based radar demonstrator: concept and field trials

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Abstract: This work shows the concept, performance, and field-trials of the first photonics-based radar. The comparative in-field experiments in aerial and naval scenarios against a state-of-the-art commercial system show the photonics potentials in enabling software-defined radars.

OCIS codes: (060.5625) Radio frequency photonics; (280.5600) Radar; (140.4050) Mode-locked lasers

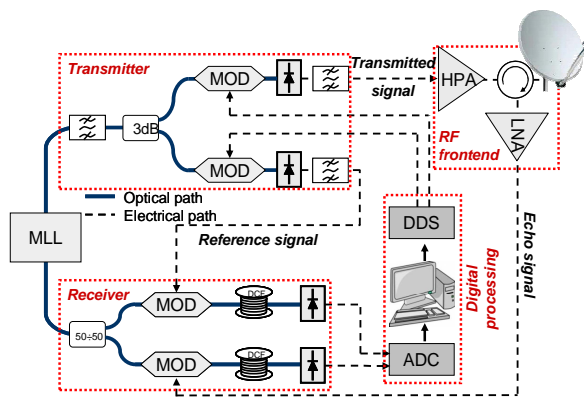
1. Introduction

The requirements of resolution, sensitivity, and flexibility of future multifunctional radar systems are pushing the development of reconfigurable and software-defined-radio (SDR) radar transceivers, capable of managing wideband waveforms over high-frequency carriers with the phase stability required by coherent pulse-Doppler processing. Thus, the evolution of future radars strongly depends on the progress of electronic digital components as the high speed direct digital synthesizers (DDSs) and the analog-to-digital converters (ADCs). So, bandwidth and precision of digital electronics represent the limit of current radar system performance. On the other hand, microwave photonics technologies promise to match tomorrow's system needs thanks to its inherent high frequencies and ultra-wide bandwidths [1]. Following this approach, the ERC-funded PHODIR project [2] has aimed at designing and implementing the architecture of a radio-frequency transceiver for fully digital radar systems, entirely based on photonics [3]. In this work, we review the architecture and the characterization of the PHODIR system, and we report on the latest field-trial demonstrations. These in-field experiments have assessed the performance and functionality of the developed radar demonstrator, through the detection of non-cooperating aerial and naval traffic and through the direct comparison with a state-of-the-art commercial solid-state coherent radar. The reported experimental results confirm the excellent potentials of the photonics approach of the PHODIR demonstrator, highlighting its high performance and unprecedented flexibility. Finally, we comment on the possible future developments of photonics-based radars, from both the technological and architectural viewpoints.

2. Performance of the photonics-based radar transceiver

The architecture of the PHODIR system is reported in Fig. 1 (left) [4]. The photonic generation of high-quality, flexible, and high-frequency RF signals exploits the heterodyne detection of modes from a mode-locked laser (MLL). The radar waveform is generated at a low intermediate frequency (IF) by a DDS, and modulates the MLL signal in an electro-optical modulator. The optical signal (composed of original MLL modes and new sidebands) is then detected by a photodiode (PD), and a radio-frequency (RF) filter selects the desired beating frequency without resorting to electrical mixers. Hence, the carrier frequency can be arbitrarily chosen as an integer multiple of the pulses repetition rate, plus the digitally generated and highly stable IF that holds the radar waveform and guarantees a continuous tunability. The filtered RF signal is then sent to a high-power amplifier to be transmitted from the antenna. Once the radar signal has been back-scattered from a target, it is received by the antenna, amplified, and filtered. Then the received RF waveform is used to modulate the signal from the MLL (optical sampling), generating replicas of the detected signal spectrum as sidebands of the MLL modes. Finally, a PD detects the optical signals and performs the down-conversion of the received echo from the RF frequency back to the original IF, again without electrical mixers. An ADC eventually digitizes the down-converted signal at IF. The proposed architecture therefore exploits a single MLL for both the radar transmitter and receiver. Besides the radar pulses, the photonic transmitter also generates a continuous-wave reference signal which is used to implement a coherent radar deriving the targets' speed.

The photonics-based transceiver (without an RF front-end) has been characterized in a laboratory environment, and compared with the performance of state-of-the-art electronic radar transceivers [4]. The advantages of the photonic approach are evident in the extreme flexibility in the generated carrier frequency ranging up to 40GHz (while electronic radars have fixed frequency), in the arbitrary modulation capability, and in the precision of the digitization for any input frequency (effective number of bits (ENOB)>7 up to 40GHz, while electronic transceivers guarantee a direct digitization with ENOB<8 only up to 2GHz). These are fundamental features for enabling the SDR paradigm in future radars.



Parameters	PHODIR	SEAEAGLE
Peak Power	50W (@ WR90)	100W (@ WR90)
RF frequency (MHz)	9880÷9920 (continuous)	9300÷9920 (step)
Max bandwidth	40MHz	40MHz
Noise figure	8dB	5dB
MDS	-87dBm@40MHz BW	-90dBm@40MHz BW
Max processing gain	31dB	34dB
Frequency accuracy	120ppm (13fsec)	100ppm (10fsec)
Max range	18NM (cargo target)	24NM (cargo target)
Pulsewidth	0.2÷10μsec	50nsec÷26μsec
PRF	1÷12KHz	661÷1112Hz
Modulation format	Any	Chirp

Fig. 1. Left: PHODIR transceiver architecture. Right: Specifications of the PHODIR demonstrator, compared with the *SEAEAGLE* by *GEM elettronica*.

3. The radar demonstrator and the field trials

To validate the PHODIR transceiver in a realistic surveillance operation, a radar demonstrator has been implemented, adding to the photonics-based transceiver an RF front-end (RF circulator, switches, amplifiers, filters, and monostatic antenna) for a signal carrier at 9,900MHz, with a maximum instantaneous bandwidth of 40MHz due to the bandwidth of the exploited RF filters. The main specs of the demonstrator are reported in Fig. 1 (right). This demonstrator has been tested in several field trials.

The first field trial has been run from the lab roof, pointing at the air traffic from the close airport of Pisa, Italy [4]. The system was set to transmit a standard pulse train with 1μs pulsewidth (PW) and 10kHz pulse repetition frequency (PRF), for a range resolution of 150m over 15km of unambiguous distance. The coherent integration time (CIT) was 20ms, corresponding to about 200 integrated pulses for a Doppler resolution of 0.55m/s (2km/h) over an unambiguous velocity of 76.4m/s (275km/h). The transmitted peak power was set to 20W. These features have allowed the correct detection of civilian airplanes during the take-off/landing maneuvers.

A second trial has been run in a maritime scenario at the port of Livorno, Italy, giving the opportunity to exploit the full-digital capabilities of the demonstrator [5]. The settings of the radar have been changed to fit two different case studies. The first one aimed at a long-range detection, targeting the cargo ships and ferries offshore. The radar pulse was modulated with a 13-bit Barker code allowing a range resolution of about 11m, and the CIT was extended to 100ms for a Doppler resolution of 0.15m/s. This way it has been possible to detect the slow speed as well as the shape of the targeted ships. Then the system was set for the short range detection of maneuvering targets into the harbor area. The PW was shortened to 400ns and compressed with a 13-bit barker code, for a range resolution of about 5m. These measures have allowed to clearly detecting even small boats moving within the harbor. It is important to note that these maritime measurements have not registered any spreading of the detected Doppler speed, usually present due to the sea clutter, in accordance with the high stability of the generated signal.

Recently another maritime field trial has been run in cooperation with *GEM elettronica* in the area around the port of San Benedetto del Tronto, Italy, where the detections obtained by the PHODIR radar system have been compared to the ones by a commercial coherent radar in the X band, the *SEAEAGLE*, the top-product of *GEM elettronica* [6]. A preliminary lab comparison (see Fig. 2 right) has highlighted very similar fundamental features for the two systems: the minimum detectable signal (MDS) has turned out to be -90dBm for the *SEAEAGLE* and -87dBm for the PHODIR, while the noise figure has been measured to be respectively 5dB and 8dB. These must be considered as promising results, being the PHODIR system at a demonstrator stage only, realized with standard, non-dedicated photonic devices. Moreover, the photonics-based radar has shown a superior flexibility (PW, PRF, pulse modulation type) and bandwidth. Then the two systems have been directly compared in a field trial, acquiring the same maritime environment. The two radars have been set to transmit a linear chirp with a frequency deviation of 10MHz over a PW of 1μsec and a PRF of 10kHz, with a transmitted peak power of about 50W. The CIT has been set to 7.5ms, corresponding to the rotation of 1° of the two similar rotating antennas exploited in the trials. The resulting resolution has been 15m and 2m/s. Both the systems have scanned the area around the port. Fig. 2 (A) shows the PHODIR detection trace overlaid to the satellite map of the port: the coastal area and the harbor shape are well represented, including the breakwater lines and a small boat at about 0.42 nautical miles (NM) with a detected radial velocity of 5 knots (2.57m/s). Fig. 2 (B) and (C) report the plan position indicator (PPI) plots for the same scene taken by the PHODIR and *SEAEAGLE* radars, respectively. While the PHODIR system under the current

settings can analyze a range of 8NM, due to its fixed settings the *SEAEAGLE* can analyze a range of 6NM only. Therefore, while the PHODIR has detected 5 targets, the *SEAEAGLE* has reached 4 of them. Besides this, the plots show a perfect matching in the visualized scenario.

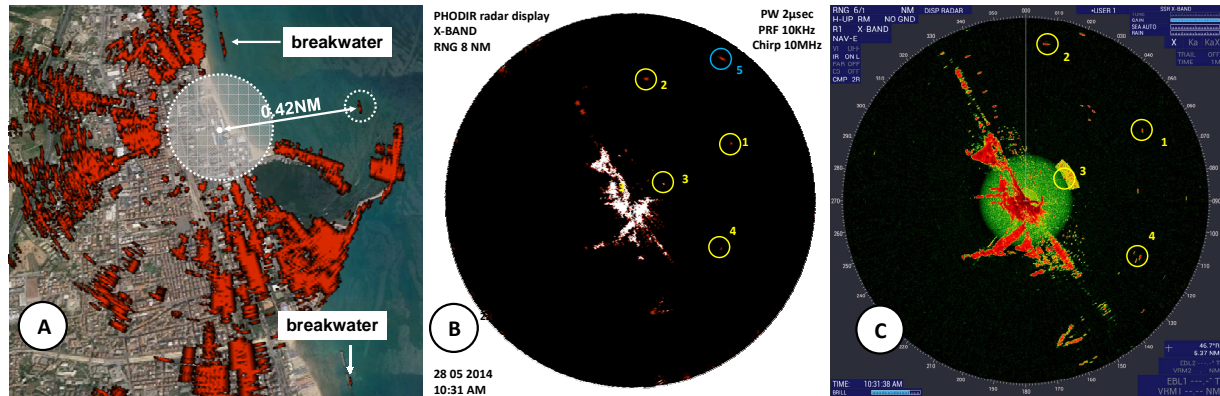


Fig. 2. (A) PHODIR radar detection of the area around the port of San Benedetto del Tronto, Italy. (B),(C) Comparison of the plan position indicator plots from the PHODIR and *SEAEAGLE* systems respectively, acquiring the same scene.

4. Future developments

The reported characterizations have demonstrated the unprecedented flexibility of the photonics-based radar transceiver, which allows enabling the SDR paradigm. Besides this, the results from the field trial experiments have assessed the good performance ensured by the radar demonstrator, which has turned out to be comparable with state-of-the-art commercial systems.

Several architectural developments can be imagined starting from the PHODIR scheme, further exploiting the potentials of photonics. For instance, we have already proposed to exploit the wide available optical spectrum to implement a photonic beamforming network feeding a phased arrayed antenna [7]. Moreover, the photonic core of the system could be doubled to implement a synchronous dual-frequency radar exploiting a single high-stability laser source [8]. Another possibility enabled by photonics is the implementation of a hybrid radar/lidar system, with peculiar synchronous and multispectral capabilities.

Even better performance is expected from the implementation of the PHODIR architectures through integrated photonic techniques. In fact, the specific design of photonic components as tunable narrowband filters can boost the system flexibility much further (for instance, avoiding the need for fixed RF filters). Moreover, an integrated realization is also expected to reduce the size and weight of the photonics-based radar transceiver, and to increase its stability (lower sensitivity to thermal fluctuations and vibrations).

Finally, the developments of the photonics-based radar transceiver can positively affect the RF transceivers at large, i.e. not confined to the radar application [9]. The photonic approach is in fact expected to allow the establishment of a new paradigm of RF systems, with improved performance, unprecedented flexibility, and reduced size and weight.

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