Photonics-enabled 2Tx/2Rx coherent MIMO radar system experiment with enhanced cross range resolution

M. Maresca[1], D. R. Sanchez Jacome[1,4], L. Lembo[2,3], F. Scotti[2], G. Serafino[1], A. Malacarne[1], C. Rockstuhl[4], P. Ghelfi[2], A. Bogoni[1,2]

[1]TeCIP – Scuola Superiore Sant'Anna, Via Moruzzi 1, 56124 Pisa, Italy
[2]CNIT – National Photonics Labs, Via Moruzzi 1, 56124 Pisa, Italy
[3]Vallauri Institute, Centro di Supporto e Sperimentazione Navale (CSSN), Livorno, ITALY
[4]Karlsruhe Institute of Technology, Germany
e-mail: antonella.bogoni@cnit.it

Abstract: Photonics enables a multi-target experiment of coherent MIMO radar. It confirms that coherence introduces almost one order of magnitude improvement in the cross-range resolution. Simulations demonstrates the coherent bi-band operation benefits on the system performance.

OCIS codes: 250.0250 Optoelectronics; 280.5600 Radar;

1. Introduction

For the most of its applications, remote microwave sensing will require innovative *multiband and distributed* radars, for collecting complete information on the scene under observation, thus being able to precisely detect, recognize and classify the different targets.

(i) Multiband radars, working in different radio spectral regions with different features, will increase the system detection capability and reliability, along with its robustness to the environmental conditions. Coherent data fusion among multiband detections permits to exploit all the acquired information, increasing the system precision. For this reason, coherence among bands will be largely sought. As a fact, conventional radio frequency (RF) electronics have an intrinsic narrow band and lack in flexibility; therefore, multiband radars can be obtained only using several independent single-band apparatuses. In these cases, the coherence among data is usually reconstructed digitally through heavy synchronization algorithms with high computational complexity in the radar processing.

(ii) Distributed multistatic or multiple input-multiple output (MIMO) radars represent a breakthrough overcoming the traditional concept of stand-alone, local radar. A MIMO radar is defined as a radar system employing multiple transmit waveforms and having the ability to jointly process signals received by multiple antennas [1]. Their enormous potentials stands in that they allow observing the same scene from different viewpoints, with benefits when trying detecting targets characterized by high angular radar cross section variability (i.e. stealth targets). Moreover, MIMO radars permit to increase the cross-range (i.e. angular) resolution. In fact, in a monostatic radar the range resolution is determined by the bandwidth of the transmitted signal, whereas the cross-range resolution depends on the antenna beam aperture and the target distance; while MIMO radars exploit spatially distributed information to achieve an excellent cross range resolution independent of antenna features. Moreover, MIMO systems allow to better estimate the target velocity vector (a single radar can detect the Doppler frequency shift due to radial movements only). Finally, the coherent elaboration of data collected from different positions can also contribute to increase the radar network detection capabilities. Nowadays, multistatic radars do exist, but integrated operation is still inadequate: each interconnected system performs a local processing and then sends the pre-elaborated data to a central processor in charge of implementing data fusion, inevitably losing a certain amount of information. Unfortunately, MIMO radars with widely separated antennas have two main issues: they need high capacity data links to send raw data from the multiple antennas to the central processor; and they require extremely precise time synchronization and consequently high phase coherence between all the components of the distributed system. Finding an RF solution to these problems is challenging, especially for largely distributed systems. A solutions only in co-located scenario, has been presented [2].

Recently, the use of photonics has been demonstrated for radar signal generation and elaboration, providing extreme frequency flexibility, coherent multiband operation and software defined radar configuration [3]-[5]. Photonics can also enable coherent RF signal distribution. The benefits of the coherent distributed sensor operation have been already numerically investigated [6],[7]. Moreover, the latest advances in photonic integrated technologies enable the concept of photonics-based radar on chip, with enormous advantages in terms of size weight and power consumption.

In this paper, the first complete experimental and simulative investigation of photonics-based coherent MIMO radar system in presence of multitargets is reported, demonstrating a cross-rage resolution improvement of almost one order of magnitude. A numerical analysis on more complex scenarios proves that the photonics-enabled coherent multiband operation is another fundamental system feature in MIMO radars to also reduce side lobes.

2. Photonics-enabled coherent MIMO radar system

Photonics allow the generation and elaboration of multiple radar signals (also in different bands) through a single local oscillator, consequently guaranteeing the intrinsic coherence among the signals. Moreover, as reported in Fig. 1 (A), signals can be generated in a single central unit and delivered to several (M) widely distributed antennas by means of optical fibers enabling distributed and coherent radar systems. Photonics ensures unprecedented frequency flexibility and phase noise stability [3]-[5], and optical fiber represents a very effective and wideband transmission link. Therefore, a photonics-based MIMO radar can be composed of a central photonic core and several antenna sites, with the photonic core optically distributing the RFs (RF_1…RF_N) signals via optical fiber to all the antennas. A merging of the benefits of photonics-based distribution and photonics-based up- and down-conversion for RF signal generation and detection [6], can be obtained, as reported in Fig. 1 (B), implementing distributed photonics-based up- and down- conversions architecture with a stage in the central unit, shared among all the radar heads (RHs), and a further dedicated stage in each RH. From a processing point of view the coherent MIMO elaboration corresponds to a digital beamforming (where coherence is fundamental for the cross range resolution enhancement) using a sparse antenna array. The sparse configuration of the antenna elements (i.e. the distributed RHs) results in the presence of side lobes that seriously affects the system performance i.e. false target detection and error probability. However, these side lobes can be reduced acting on the geometry of the radar system and on the number of RHs. Here we numerically demonstrate that multiband operation can also reduce the side lobes without changing the system geometry and the sensor number (i.e. without hardware increasing). The additional processing complexity for fusing the multiband acquisitions, is limited due to the intrinsic coherence among bands, assured by photonics.

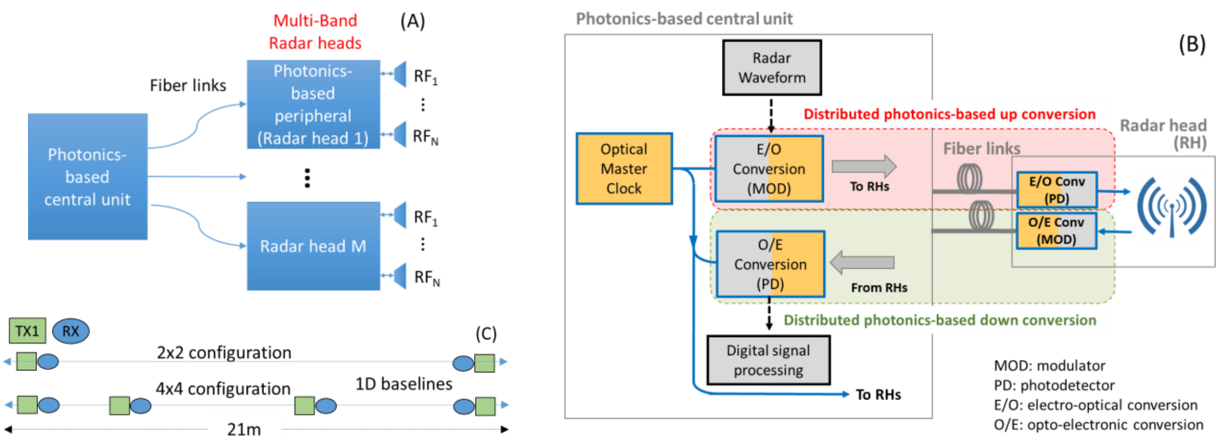

Fig. 1. (A): Working principle of a photonics-based coherent MIMO radar network; (B): detailed structure of a photonics-based distributed up- and down-conversion; (C): used 2x2 and 4x4 sensor configurations.

3. Photonics-enabled coherent MIMO radar system implementation and results

The system is implemented in a 2x2 (2 transmitters, 2 receivers) configuration with the sensors placed along a 21m-long 1D baseline which enables a 2D imaging (i.e. range and cross range) as shown in Fig. 1 (C). The system consists of a photonic core, and two RHs with one TX and one RX each. The photonic core develops around the optical master clock, which is implemented by a solid-state mode-locked laser (MLL). The MLL is a pulsed laser, with a repetition frequency f_{MLL} = 400 MHz. This clock allows generating RF carriers with extremely low phase noise, thus implementing high-quality RF up-conversion and down-conversion [8]. At the transmitter side, the radar signal, which is digitally generated at intermediate frequency (IF), is first modulated on the MLL spectrum by an electro-optic modulator (MOD), optically distributed to the RH and then photodetected (PD), generating many replicas each centered at $k{\cdot}f_{MLL}\pm$ IF, with k positive integer [3], [4]. This way the photonics-based up conversion is carried out. The desired RF output carrier frequency f_{RF} can be selected by means of a microwave filter, centered at f_{RF} and with bandwidth $\geq B$, where B is the desired signal bandwidth. The employed band-pass filters are multi-cavity filters with -3 dB bandwidth of 100 MHz and centered at f_{RF} = 9.7GHz. After proper amplification and filtering, the radar signal is transmitted by the antenna. The employed antennas at the TXs are ultra-wideband Vivaldi-shaped horn antennas with about 50° half power beam width aperture and 12 dBi maximum gain. The detected radar echoes, received by the RHs antennas, are amplified and pass-band filtered. The RXs are equipped with antennas similar to those of the TXs. For the down-conversion the RF signal is E/O converted by modulating the MLL (sent to the RH by dedicated links), then transmitted back to the photonic core and O/E converted at the PD. It generates replicas of the RF signal at $k{\cdot}f_{MLL} \pm$ IF, including the down-converted replica at IF (for $k = 0$) [9]. Here f_{IF} = 100 MHz. After this operation, the signals from each RX are low-pass filtered and fed into a two-channel acquisition system, where they are digitized by an analog-to-digital converter at 400 MS/s per channel.

The connections between the photonic core and the RHs are realized through spans of single-mode fiber (SMF). The two RHs are time domain multiplexed through the use of an optical delay line consisting of a 1 km-long SMF spool inserted just before the TX of RH2. The experiment has been carried out using two cylinders in metal net suspended to small quad-copter drones as targets, 3m spaced from each other, at a range distance of ≈15-20m. Non-coherent and coherent MIMO radar processing tools has been developed as reported in [9]. The same processing tools have been used for a simulative analysis to confirm the experimental results and to investigate more complex scenarios, in particular to investigate the impact of the sensor number and of the multiband operation on the system performance.

Fig. 2 shows the experimental range/cross range map using a non-coherent (a) and coherent (b) MIMO processing. It is well evident that the cross range resolution is improved thanks to the coherence allowing to distinguish the two targets at 3m each other. The used antenna aperture corresponds at the target distance (~18m) to a cross range resolution of >15m. The non-coherent MIMO processing allows to reduce it down to 10m (not enough to distinguish the two targets), while the coherent MIMO processing introduces a further significative improvement, down to 3m, corresponding to a >x5 enhancement compared to the monostatic radar case. However, side lobes are not eliminated. Fig. 2 (c) reports the coherent MIMO simulated result demonstrating a very good agreement with (B). The simulation tool has been also used for demonstrating the impact of the bi-band operation (X band=9.7GHz and S band=2.6 GHz) in significantly reducing the side lobes (fig. 2D), exploiting the fusion of the coherent bi-band detections. Bi-band operation has been already experimentally demonstrated in [3]. On the other hand, Fig. 2(E) numerically demonstrates similar side lobes reduction due to the increasing of the sensor number up to 4x4 (Fig. 1C). Finally in Fig. 2(D) these two approaches are merged (increased number of sensors and bi-band operation) to simultaneously guarantee a superior cross range resolution and eliminate the side lobes and optimize the system performance.

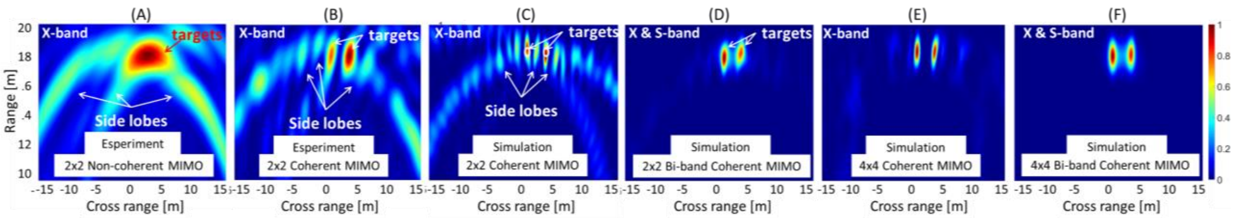

Fig. 2. Range/cross range map using a 2x2 configuration and two targets in the experimental case with X-band signal and non-coherent (A) or coherent (B) MIMO processing, in the simulative case with coherent MIMO processing and X-band signal (C) and with bi-band signals (X and S band) (D); using a 4x4 configuration in the simulative case with X-band signal (E) and bi-band signals (F)

4. Conclusion

A multitarget experiment on photonics-enabled coherent MIMO radar has been carried out and the results compared with a numerical analysis for verifying the superior cross range resolution introduced by coherent MIMO approach. Simulations also demonstrate the benefits of coherent multi-band operation for side lobes reductions. The merging of this two features (coherent MIMO and coherent multi-band operation) enabled by photonics, allows for a unprecedented radar performance.

The activity has been partially supported by SOLE project funded by NATO.

4. References

[1] H. Godrich et all, "Target Localization Accuracy Gain in MIMO Radar-Based Systems" IEEE Transactions on Information Theory, Vol. 56, N°. 6, June 2010.

[2] T.Derham et all "Realisation and Evaluation of a Low Cost Netted Radar System", IEEE Radar 2006.

[3] P. Ghelfi, et al., "Photonics for Radars Operating on Multiple Coherent Bands", invited paper, J. Lightwave Technol., vol. 34, n. 2, 2016

[4] P.Ghelfi et al, " A fully photonics-based coherent radar system", Nature Vol 507 March 2014.

[5] F.Laghezza et all, "Field Evaluation of a photonics-based radar system in a maritime environment compared to areference commercial seonsor, IET Radar Sonar & Navigation Journal, Vol 9, n. 8, 2015.

[6] G. Serafino et al., "A Photonic Approach for On-Board and Ground Radars in Automotive Applications", IET Radar Sonar & Navigation Journal, Vol 12, n.10, 2018.

[7] L. Lembo et al, "Analysis of a Coherent Distributed MIMO Photonics-Based Radar Network", EuRA*D*. 2018.

[8] G. Serafino, et al., "Phase and amplitude stability of EHF-band radar carriers generated from an active mode-locked laser," Journal of Lightwave Technology, vol. 29, n. 23, Dec. 2011.

[9] L. Lembo, et al., "In-Field Demonstration of a Photonic Coherent MIMO Distributed Radar Network," Proc. of IEEE Radar Conference 2019, Boston (MA), USA.