The photonic radar ─ the situation today and the prospects for the future

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ABSTRACT

The paper presents the main objective of the idea of a photonic radar and an example of the engineering of the first fixed photonic radar demonstrator, designed for use in air traffic control. Some issues related to the production and transmission of microwave and optical signals, as well as the frequency conversion of these signals have also been presented.

Keywords: photonic radar, radar, PhoDIR, frequency conversion

1. PREFACE

Contemporary radars are designed strictly for specific remote sensing needs. Radars have many civil and military applications, e.g. in meteorology, ground penetration (GPR), vehicle speed control. The use of radars in air and maritime traffic control is of particular importance.

The scope of this article does not include a review of solutions used in radars designed and constructed in classic electronic microwave technology, nor does it apply to all "properties of modern radars" designed and manufactured in this technology. Detailed descriptions of the structure and properties of various types of modern radars, made in classic electronic microwave technology, are described in the extensive technical and patent literature, for example [6-12].

Radars designed and constructed in this classic electronic technology are still being developed and improved. Currently, they constitute the basic core of radiolocation devices and it seems that they will be used for a long time. The presented article intentionally refers only to selected aspects that are the proverbial "Achilles heel" of classic radars. Some of these restrictions, however, can be successfully solved and overcome, but in photonic technology.

Modern radars are expected to have much higher resolutions, smaller sizes, lighter antennas, consume less energy, and above all, be very versatile. There is a belief that to meet this challenge, modern radars should operate at much higher frequencies, as well as they should be based on SDR (Software Defined Radio) technology. Traditional radars, e.g. used in radiolocation, are usually large and heavy (sometimes even very large and heavy). First of all, they feature very limited possibilities to adjust their parameters to values that should be achieved in the face of changing environmental conditions or in line with realizing a radiolocation task. Such radars completely lack the ability to quickly adjust the bandwidth or control polarization. Usually these devices are dedicated to work in one band and one polarity. In typical conventional radars, the radar signals and radar beams are formed by a variety of complex electronic techniques. All signals are produced and processed by electrical processes, i.e. using electronic components and techniques. Different types of radar use different frequency ranges - from radio to microwaves. In the microwaves range, the transmission of the signal is usually carried out through striplines or waveguides, such as metal pipes of rectangular cross-section (the transverse dimensions of which are comparable to the length of the transmitted wave or longer) or coaxial wires or dielectric rods or tubes, while the energy of the radar beam is emitted in the form of an appropriately formed electromagnetic radiation beam, while the echo signals are sent to the receiver (or receivers) by the aforementioned transmission lines.

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The properties of microwaves make it necessary to select the materials and dimensions of the waveguide path. These dimensions must be strictly matched to the range of microwaves used and must be maintained during operation. This means that the transmission line must be executed and assembled with utmost precision. Meeting the above requirements is difficult and expensive.

Many of the characteristics listed here have been identified as limitations of the radar status quo, which, together with the currently unrealistic expectations of the growing needs of radiolocation, limit the development of radars.

This has become the motivation to search for new design solutions that would make the implementation of a radar operating at even higher microwave frequencies possible. Analyses of the current state of technology have permitted to identify those factors and elements of radar that constitute a difficult barrier to overcome. The development of radars, blocking the implementation of new functions, was impeded by the technology in which the current radars are constructed. Their further effective development has become dependent on the progress of radar signal production and reception techniques, modulation strategies, frequency detection and conversion, as well as signal transmission. The progress is possible but requires a new approach to the radar problem.

Selected elements and components limiting the properties of contemporary radars

The analysis of factors limiting the parameters of modern radars shows that they mainly include the materials, elements and components from which these radars are built, as well as in the use of inefficient (in relation to today's expectations) traditional electronic technology. The limitations also result from a certain attachment to reliable, traditional system solutions. The key components enhancing the limitations of traditional radars include frequency synthesizers, analogue-to-digital converters and both up and down frequency converters. These components, despite continuous improvement in technology and the introduction of modern solutions, have been identified as sources of strong noise, the level of which increases with the frequency of operation. These components have also been recognised to have limited bandwidth and capacity. The original cause of the limited capabilities of radar systems can be found in generators, transmitters, amplifiers, microwave parts (front end), antennas, waveguides, which can only work up to a few - rarely several dozen - of GHz. To produce a radar beam radars built with the application of traditional electronic technology must first construct the radar beam from the relevant digital signals which are then converted to an analogue form, then converted upwards in the frequency domain and then transmitted via a waveguide to the antenna. While during the reception of radio echoes, the signal is sent to the receiver, where it is amplified and also converted in the frequency domain, but this time downwards, and further processed into digital form. Attempts to perform these operations on even higher frequencies (e.g. in the terahertz band) encounter invincible barriers.

In addition to the usual issues in question during the production and processing of electrical signals at terahertz frequencies, all stages of the processes involved in the generation and processing of radar signals encounter serious problems and technical complications. They concern both, the transmission, receiving, and transmitting lines, as well as elements and components that are part of amplifiers, generators, mixers, etc. Meeting even some of the requirements calls for a much wider bandwidth and an even better signal-to-noise ratio. In view of the present state of electronic technologies, it is practically impossible to overcome these difficulties. Due to the need for precise radar systems, e.g. for air traffic control, and the ominous inability of the current electronic technologies to meet the expectations set out for radars, the concept of a radar free from existing limitations was born. Creating a radar of this type requires a radical change in the original concept, structure and construction of radar as well as the development of breakthrough techniques of signal production and processing, and above all calls for new elements and components. Photonic techniques may be the answer.

The conception of a radar based on the idea of photonic systems

Radars operating in millimetre bands require efficient transmissions with the widest possible bandwidth. Fibre optic networks used to transmit electromagnetic energy on optical frequencies may be an example of a successful solution that overcomes some of the difficulties in microwave signal transmission. However, the creation of such networks requires high modulation frequencies, detection and speed of signal transmission. As, according to the state of the art technology, the technical possibilities of traditional solutions are practically exhausted or cause serious difficulties, it seems that the remedy for this state of affairs may be the transmission of signals in the optical range. It appears to be a relatively easy task with the use of fibre optic techniques. To implement the aforementioned idea it is at least required to have:

- Optical sources of sufficient performance (e.g. mode-locked lasers),
- Optical signal modulators (e.g. optical fibre, electro-optical modulators),
- High-speed photodetectors (e.g. PIN or MSM diodes (GaAsN/GaAs)).

The idea of a photonic radar is nowhere close to the traditional radar and does not correspond to the idea of LIDAR. The term "photonic radar" originated in the idea of replacing all radar systems using electronic technology with photonic systems. The photonic system consists of subsystems and elements transforming modulated signals from the electrical field into electromagnetic (optical) signals and vice versa.

These mainly include:

- Mode-locked lasers (MLL), distributed feedback lasers (DFB)

  These devices produce laser radiation called the *optical frequency comb*. It assumes the form of a spectrum consisting of a sequence of stable, evenly distributed and ultra-short femtosecond laser pulses. The operating principles of MLL lasers are described in numerous works. In brief, it consists in a compensation of the chromatic dispersion of laser radiation, i.e. a compensation of the effects resulting from the interaction of light with electrons of the medium in which this light is being propagated, as well as a compensation of interference or geometric effects, which affect the changes in the phase and group speed of pulses of the light propagating in this medium depending on the optical frequency of light.

- Systems converting the electromagnetic radiation frequency. These systems are based on the so-called optical heterodyne. Optical heterodyne is a process using the effects of summing up the signals of modulated laser beams. The conversion systems are parts of systems that produce optical signals, e.g., in systems that convert these signals into electrical microwave signals. The idea of using this method to obtain electrical microwave signals is illustrated in Fig. 1.

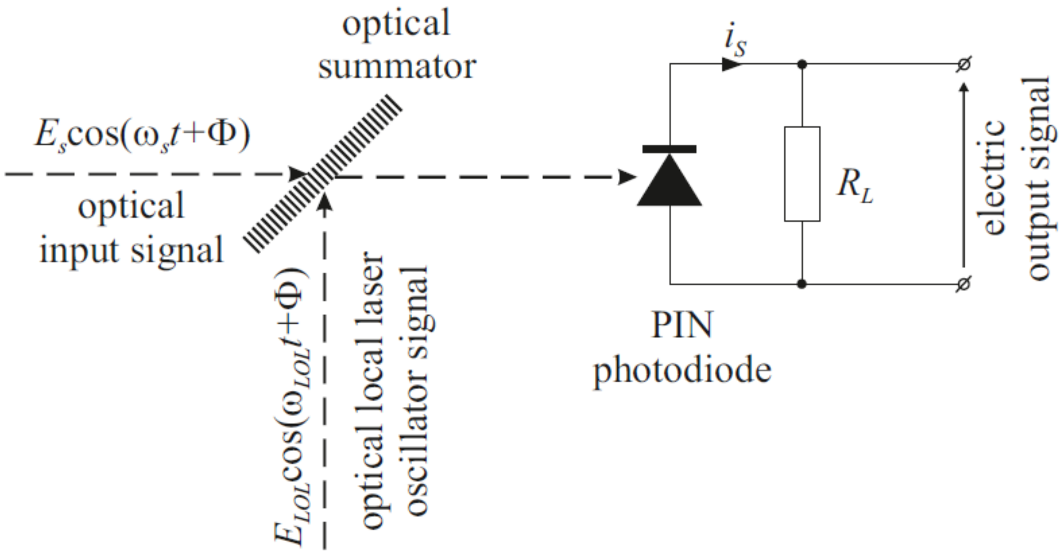


Fig. 1. The idea of optical generation of electric microwave signals

Other elements needed include the pin and MSM photodiodes, optical fibres, optical modulators, optical phase shifters, and beam dividers through which the signals are processed and then the required waveforms are formed to produce the radar microwave beams and to receive the echoes, and finally obtain the electrical target information signals.

In the transmission mode, the generation of an electrical output microwave signal is accomplished by processing an optical signal derived from the optical heterodyning of an input signal (carried by an optical beam modulated by an input signal) with another optical signal (also carried by another optical beam, but modulated by a different frequency signal), called the local laser oscillator signal, in which the signals carried by both laser beams, after summation, ensue in another modulated optical beam, but with parameters resulting from the superposition of these beams and then, as a result of the illumination with such a photodiode beam, an electric microwave signal is obtained at a frequency depending on the frequency of the heterodyne product of the input signal. This signal, when amplified, can be emitted by a conventional antenna. In the receiving mode, the delay between the signal transmitted and received (deflected from the target) provides the information making it is possible to determine the distance to the target - the received echo signal modulates the laser and in the reverse process converts it into an electric signal.

The modulator

In the photonic systems, microwave signals, as well as internal control signals, are transmitted through optical beams. Modulated optical beams are produced by direct laser modulation or by external modulation. The electro-optical modulators based on the Pockels effect are used in the range of very high modulation speeds and frequencies (e.g. in materials such as LiNbO3 or organic polymers). The disadvantage of the modulators of this type - despite the fact that they reach a band of several dozen GHz - is that they require control signals from several hundred volts to even several dozen kilovolts. In terms of convenience, the electro-absorption modulators based on the Franz-Keldysh effect are much easier to use. For a similar modulation band, there is a need for only a few volts of amplitude per signal. Modulated beams are also produced with the application of Mach-Zehnder's interferometers (Figure 2).

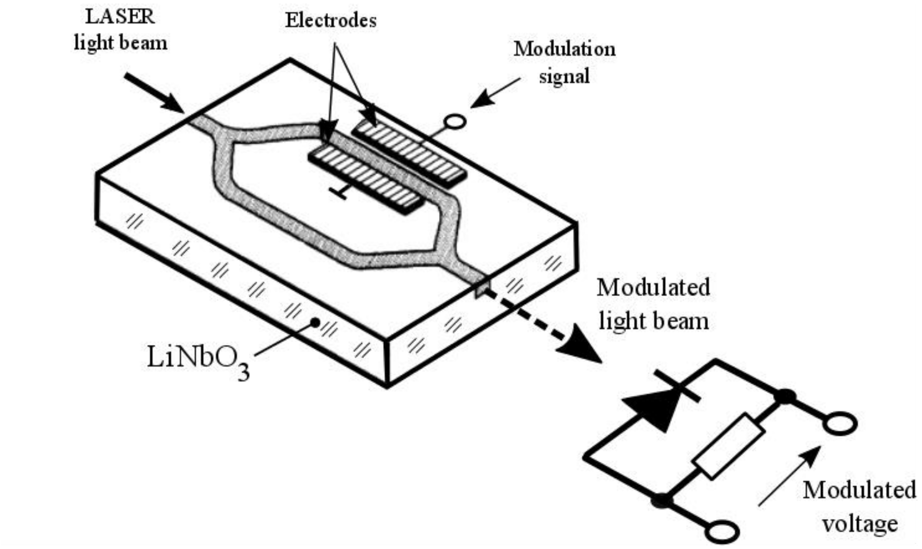


Figure 2. Idea of the Mach-Zehnder's fibre optic modulator interferometers

Fibre optic microwave signal transmission

In radars built in the traditional electronic technology, the two-way transfer of produced and received radar signals is carried out by coaxial lines and waveguides. Such networks are characterised by a number of imperfections, e.g. large size, weight and cost, but also low resistance to electromagnetic interference as well as high dispersion and low capacity.

The idea of the fibre optic microwave signal transmission is shown on Figure 3. Signals can be sent simultaneously in both directions and at different wavelengths

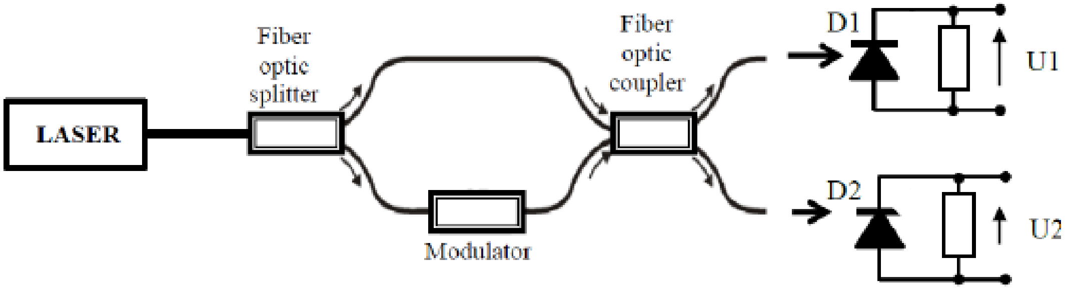


Figure 3 Idea of the fibre optic microwave signal transmission

In comparison to traditional transmission lines, the photonic networks are characterized by smaller sizes, lower weight and costs, as well as very high resistance to electromagnetic interference, and also very low attenuation, low dispersion and high capacity. Photonic networks permit two-way and duplex microwave signal transmission.

The PhoDIR system

Although the possibilities of producing and detecting microwave signals in photonic systems were studied separately, i.e. on separate transmitting and receiving devices, the implementation of the above, but in one transmitting and receiving device has not been studied and considered until recently. Combining all photonic components in one device is the essence of the PhoDIR (PHOtonics-based fully DIgital Radar) system, the world's first photonic digital radar demonstrator. The schematic diagram of the development of this system is provided in Fig. 4.

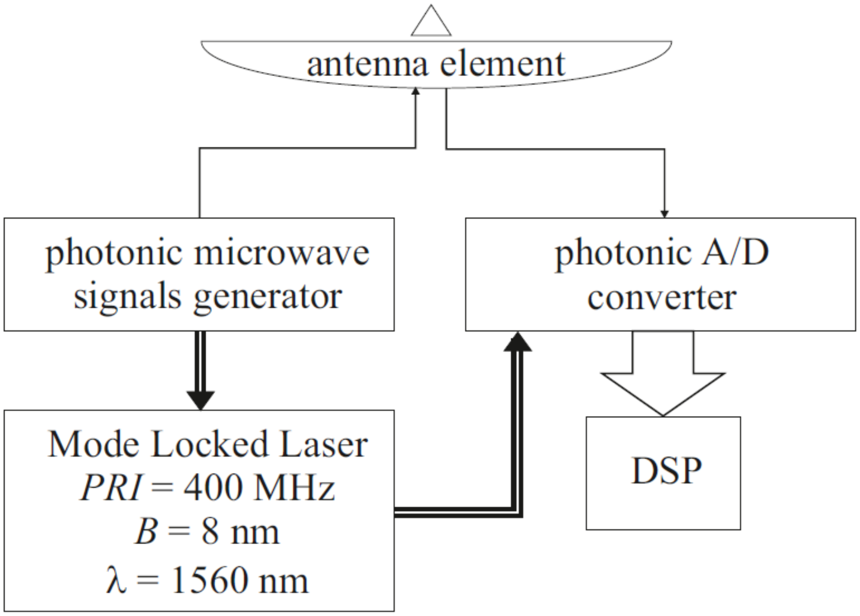


Figure. 4. The schematic diagram of the PhoDIR system development

The information found in [1] sets out that the PhoDIR system is characterized by excellent parameters in relation to analogous systems implemented in the traditional electronic technology. It has more than 10 times less phase noise (better than 140 dBc/Hz). The heart of this system is a photonic transceiver, which produces microwave radar signals by a single, tunable pulse laser, while the echo of the signals is received by a photonic receiver. The PhoDIR system has been designed to work in real time. The limit value of the frequency of the signals supported by this method depends on the photodiode band. The PhoDIR system concept is shown in the block diagram (Fig. 4). The block diagram is shown in Figure 5.

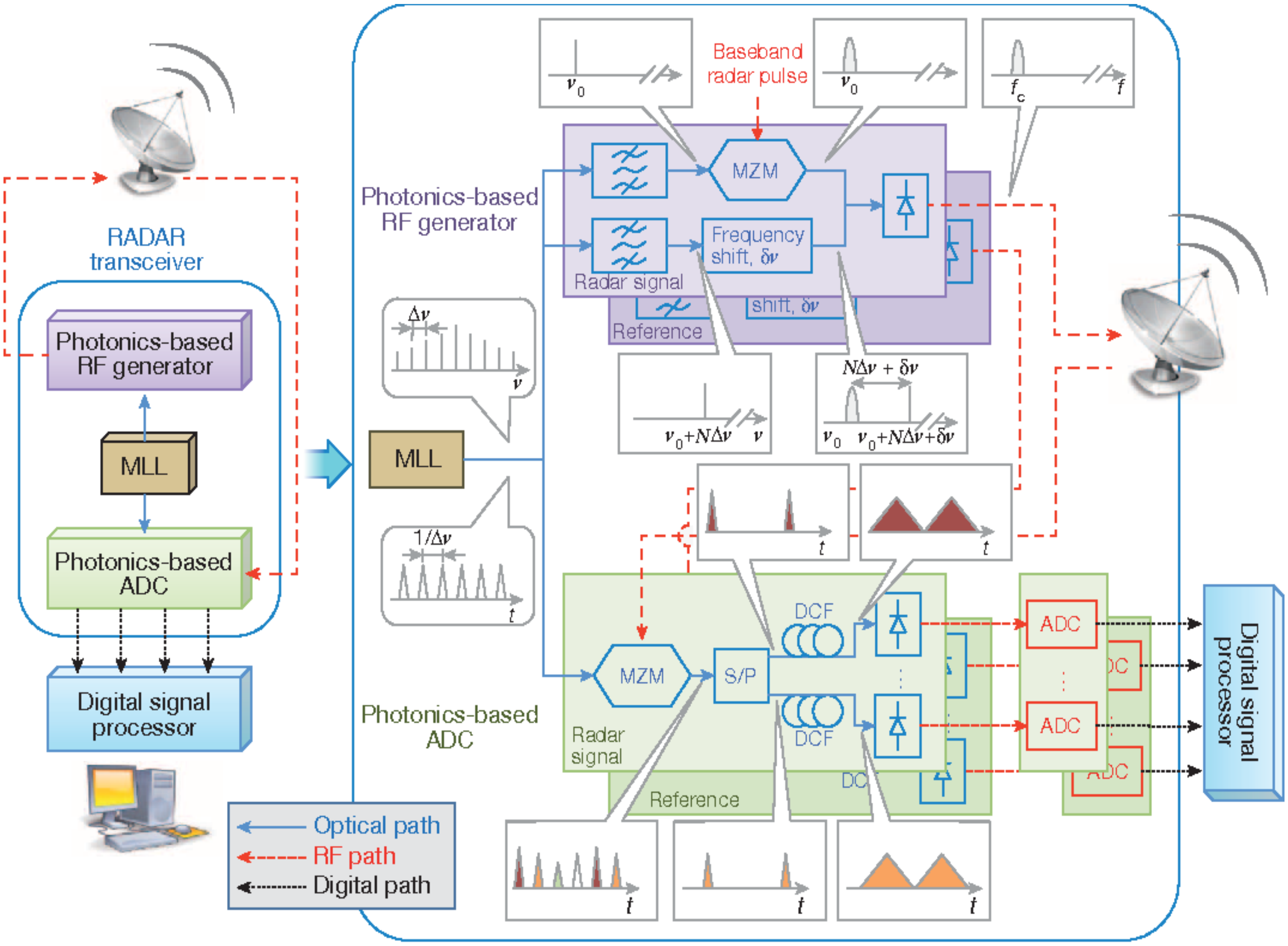


Figure 5. PhoDIR system block diagram [1]

The PhoDIR and field trial tests has been presented in the joint laboratory of the Photonic Network National Laboratory (LNRF) of CNIT and the Institute of Communication, Information and Perception (TECIP) of the Sant'Anna School of Excellence. The general view of the entire device shows Figure 6.

Figure 6 General view of the entire device [6].

By eliminating the need to convert the frequency of signals (up or down), a significant reduction in undesirable components has been achieved and, in addition, we have gained a much higher capacity and efficiency at a level unattainable for electronic systems and at carrier frequencies significantly above 2 GHz.

EVOLUTION OF PHOTONIC RADARS

Due to the fact that a radar is practically the only remote sensing device with the use of which it is possible to carry out the imaging of distant targets, in virtually all weather conditions, they become increasingly indispensable in various areas. Despite many construction, system and programming efforts, the achieved parameters of radars built in conventional electronic technology are not able to solve the problems and overcome limitations, which de facto result from the existing electronic technology.

The PhoDIR system mentioned above - a radar implemented in the photonic technology is an example to radically improve the parameters and performance of radars.

This system, although much smaller than the ones constructed in conventional technology, is still quite large.

Much smaller radar devices were obtained in the development of photonic radar for use in handheld scanners [7].

The structure of the is shown on figure 7.

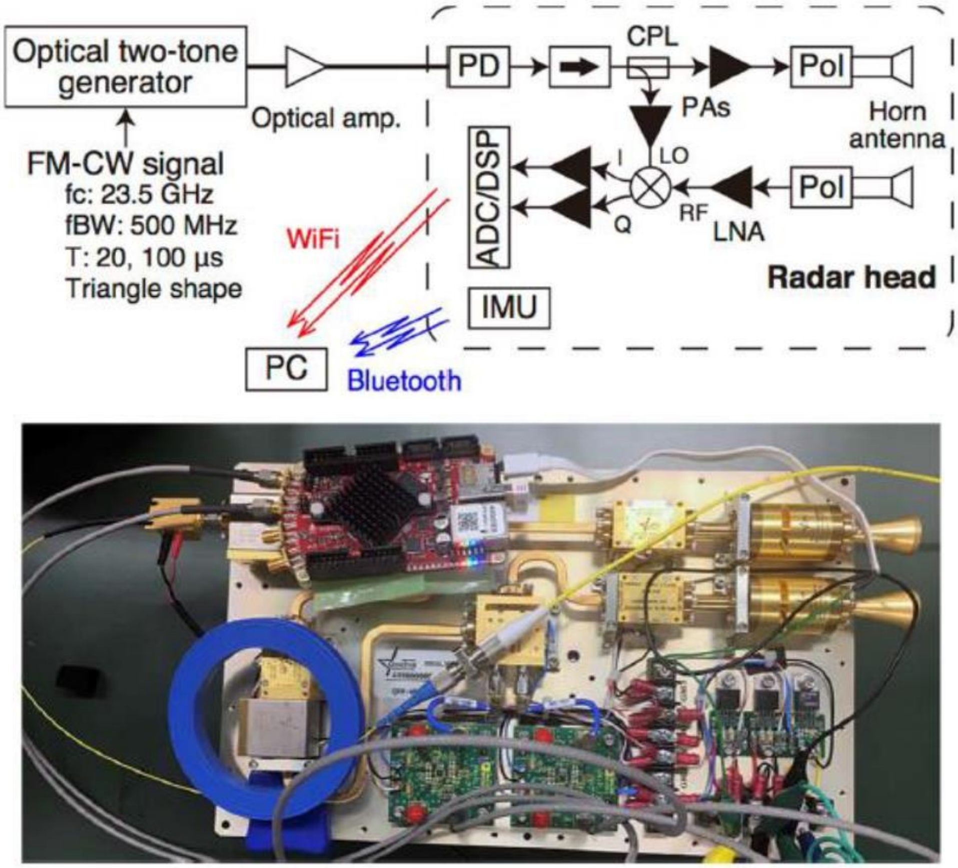


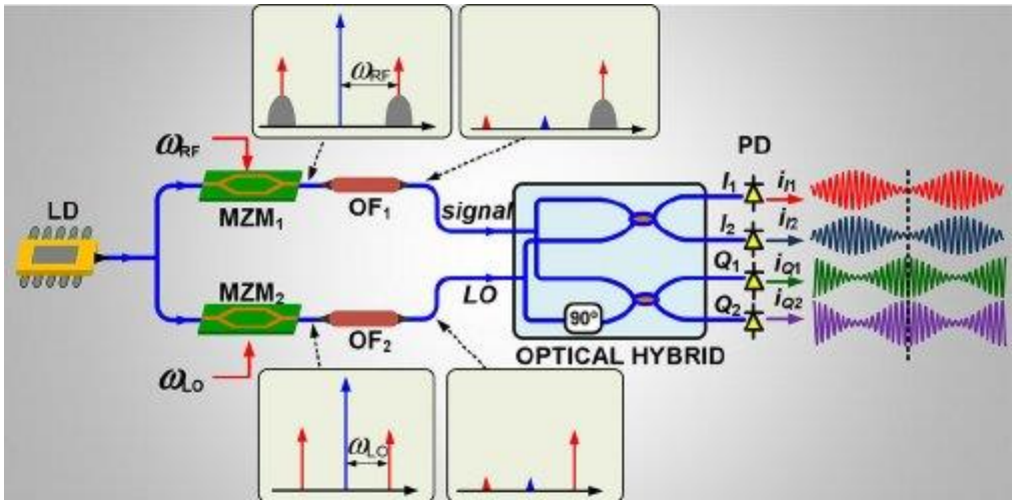
Figure 7. Schematic diagram and view of a fiber-remoted radar system [7]

The pressure of growing expectations and needs to ensure that unmanned aerial vehicles, autonomous vehicles and even mobile navigation devices can also be reliably navigated requires the miniaturisation of radars as well. This means that radars must be transformed into much lighter and smaller devices that consume less power and have a much higher resolution than today.

In the view of this, the technology of monolithic microwave integrated circuits (MMICs), produced e.g. in gallium arsenide (GaAs) and operating up to about 300 GHz, also appears insufficient for radar imaging for small target detection. In order to achieve high resolution it is necessary to have the highest possible bandwidth, and the bandwidth of even 1.5 GHz are insufficient, because the resolution is limited to 10 cm.

The trend of miniaturization and development of photonic radars is illustrated by a photonic radar built as a miniature chip on a silicon plate [4].

The system contained a broadband signal generator and a receiver integrated in one chip. This solution permitted for full Ku-band imaging with a resolution of 2.7 cm and an error value of less than 2.75 mm.



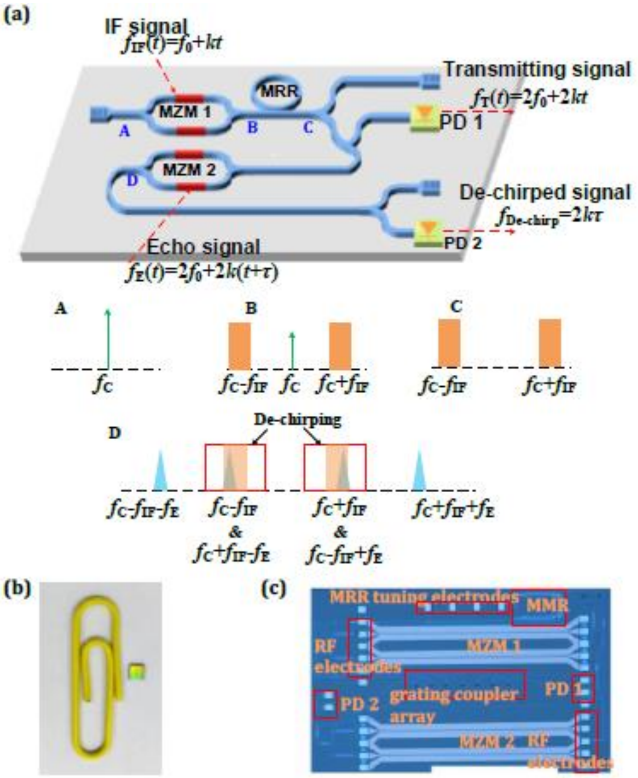


Figure 8. (a) The schematic of the chip-based integrated photonic radar (MZM: Mach-Zehnder modulator; MRR: micro-ring resonator; PD: photodetector; (b) The picture of the of the chip-based integrated photonic radar (paper clip as paper clip as referenz scale), (c) zoom-in view of the photonic radar chip [4].

The photonic technology methods of coherent optical processing to simultaneously sensing the frequency radio waves and also angle of their arrival has been presented in paper [5].

The presented method shown that signals captured by a distributed antenna array may be successfully up converted to optical domain by the using electro-optic modulators directly coupled with the individual antenna elements.

The method of spatially coherent up-conversion of radio-frequency (RF) waves to optical beams, used in tomography, creates potential possibility for radar based on signals carried by optical fibbers with only one laser source, used to feed all the modulators.

The development of photonic radar seems to be moving in two directions - towards radars used for precise observation of multiple targets at once (e.g. radiolocation) and the miniaturized imaging radars for mobile applications.

Conclusions

Microwave photonics is a field of technology synergising several disciplines such as: optics, microwave engineering, electronics, optoelectronics, computer science and material engineering. Building a photonic radar requires a team of experts experienced in these disciplines. Among the numerous issues related to the implementation of the photonic radar project, the key issues are the production and transmission of signals, both in the microwave and optical range, as well as the frequency conversion of these signals. The photonic techniques make it possible to process and transmit signals in an ultra-wide band, which is practically impossible in conventional electronic technology.

The operations impossible to carry out in the electronic microwave systems in the radio frequency range are made possible in the PhoDIR system.

In conclusion, the parameters of photonic radars may significantly exceed the parameters of radars implemented in the conventional electronic technology. A clear example of the superiority of photonic technology is the problem-free implementation of ultra-fast sampling (in the traditional technology only up to about 1 GHz, and photonic technology up to several THz) as well as the fact that photonic solutions do not encounter problems associated with rapid synchronization of signals.

The main features of a photonic radar include the lack of electric microwave oscillators, an easy production of microwave signals by using the optoelectronic oscillators, very high stability and tenability (up to several dozens of GHz).

Achieving a very high degree of distance differentiation has been gained due to the wide band and the speed of the generators' tuning. Another great advantage of photonic solutions in radars is a very low heat signature. The superiority of a photonic radar over electronic radar is also reflected in a much greater resistance of the photonic system to interference. Photonic solutions thus eliminate the electronic systems susceptible to interference.

Due to the fact that the photonic radar signals of microwave frequencies are not sent by classical transmission lines but by fibre optic networks, these signals are not subject to serious destruction. An additional benefit is the possibility of bidirectional transmission of information and carrier. The great advantage of photonic systems is their resistance to electromagnetic pulse (HPEM). Photonics opens up new possibilities for radiolocation. The USA saw about 35 patent applications registered in this area, including one in 2017 [2].

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