A survey on photonics technologies for radar applications

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Abstract Photonics is a fast and galloping technology related to both microwave and optics science. Photonics is a very vast and distinctive field in recent days. Due to the enlarged difficulty of the electronics component for large bandwidth, we had to rely on the delightful photonics system. Photonics-based system came to us as a blessing in science research in this era. Software-defined photonics-based radar must be the near forthcoming next-generation necessities. This paper has a detailed study of photonics radar and how its components work. A comparative study has been presented with the traditional electronics microwave radar systems and photonics radar systems. The slow evolution of optics system and how the application has been pushed to radar, microwave and antenna systems have been described here. In this survey repost starting from the historical storyline and basics of photonics radar, the concept of radar based on photonics system and its need, then the digitized PhoDIR system invention, radio frequency signal generation and modulation, beamforming over antenna array and signal transportation, we have discussed the important architecture of photonics radar, phase control process, sampling process, transceiver modules till the radar parameter measurements and various applications of photonics radar including quantum radar. Photonics radar seemed to be a very intense and bright research study area; many practical problems and its wonderful solution have been described here. In this paper, the advancement and progression of photonics-based radar communication system accomplishments of the last decades has been shown and also discussions about future study and development of photonics radar have been presented.

Keywords Optical RF exciter · Mach–Zehnder modulator · Photonics radar · Doppler frequency shift · Beamforming · Photonic RF measurements · Quantum radar

Introduction

Radio detection and ranging (RADAR) is a system to measure and detect the range, angle, coordinate and velocity of targets. It transmits electromagnetic waves through transmitter antenna, receives the echo signal with receiver antenna and process the echo further in order to extract the targets information. In 1886, a German experimental physicist first showed that a solid body reflects the radio wave [1]. Based on their experiments, mainly two types of radars, continuous wave (CW) radar and pulsed radar, were suggested. We can have continuous electromagnetic wave transmission in the CW radar and a sequence of finite pulsed waveforms in the pulsed radar. The CW is more appropriate for Doppler measurement, while the pulsed radar is for both range and Doppler. In pulsed radar, the pulse repetition frequency (PRF) is given by

\[
PRF = \frac{1}{PRI}
\]

where PRI is pulse repetition interval. Pulse radar radiates electromagnetic waves for very short time period (micro- or nano-second) depending upon the applications, while the CW radar transmits all the time. After the transmission time, in pulse radar, the receiver gets separated from the
transmitter and looks for the echo signal [2]. CW radar is able to detect the velocity by processing the Doppler frequency shift. And moreover by modulating the radar signal, frequency-modulated continuous wave (FMCW) radar, it is possible to measure range and velocity of the target. In FMCW radar, we get the target range by

\[ R = \frac{c \Delta t}{2} \]  

(2)

where \( R \) is the range, \( c \) is the speed of light, and \( \Delta t \) is the time interval. In FMCW radar, the frequency changes increases in a linear (or stepped, triangular or staircase, etc.) pattern and by calculating the IF frequencies with first-order FFT for range, while the second-order FFT is for Doppler information [3]. Due to high power requirements in the pulsed radar particularly for the long distance measurements, the FMCW radar is the best choice [4, 5, 7]. Based on the technology and applications, the radar is classified as bistatic radar, continuous radar, Doppler radar, monopulse radar, planer array radar, synthetic aperture radar, inverse synthetic aperture radar, ground penetrating radar, walls see-through radar and foliage radar. In this survey paper, we particularly focused on a new emerging radar technology known as photonic radar.

Photonics is a part of science studies which facilitates several technologies through glowing light [8, 9]. Photon particles units the light energy and passes through lightweight and sustainable optical fibers, solid medium and/or free space [10, 11]. Unlike electrons, the photonic signals are very much noise-free and have huge channel connection capacities. In photonics systems, the achieved transmission rate is in terahertz speed; hence it can reduce the today’s internet traffic [12]. As our war field technology is increasing toward its accurately and efficiently, we need to step into the light and photonics-based technology, mainly for the radar applications. There are many advantages we can attain by introducing the photonics technology in radar applications. Inclusion of photonics technologies in the conventional radar systems gives new features to improve actual effectiveness of surveillance. Photonics-enabled multiband radar structure has the ability to operate multiple coherent radar signals simultaneously. It can do accurate target detection and high-quality radar imaging for progressive surveillance. As a result of optical modulation introducing the radio frequency (RF) generation, we can get high stability and wide bandwidth with the single compact photonic transceiver module [13]. The simultaneous detection of multiple radar signals is adaptable and accurately measurable by the photonic radar technology. Recent research says that fully digitized photonics radar waveforms are much more reliable, diverse and less complex. The development of photonic sensor technology creates the possibility to address several requirements such as (i) processing time, (ii) system volume, (iii) transmission loss, (iv) frequency tuning, (v) immunity to electromagnetic interference, (vi) high-resolution and real-time synthetic aperture radar (SAR) and inverse SAR (ISAR) imaging, (vii) more accurate and multispectral surveillance, (viii) beam-forming and DOA estimation, and (ix) detection of types/behaviors of low RCS targets.

The prime research on the photonics has been started since 1990s age, and then the initial 2000 was the era of fiber-optical communications or networking in the use for telecommunication systems as the need for internet bandwidth is increasing rapidly [14]. In the initial of 1950s, human started generating photonic power with the help of sunlight and mercury lamp, but that was not succeeded. Then, the laser research has been started since 1960s.

In 1954, Townes displays the first Microwave Amplification by Stimulated Emission of Radiation (maser) at Columbia University, collaborating with Herbert J. Zeiger and doctoral student James P. Gordon. The first technology based on Einstein’s predictions is the ammonia maser, which achieves the first amplification and production of electromagnetic waves by stimulated emission. The maser emits light with a wavelength of little over 1 cm and produces around 10 nW of power. In 1955, the society of photographic instrumentation engineers (SPIE) has been initiated after the publication of Optical Industry Directory.

In 1957, Sir Gordon Gould, graduated from Columbia University, and wrote down his thoughts for making constructing Laser in his handbook, which is recovered by the Jack Gould.

In 1958, Townes, a Bell Labs advisor, and Bell Labs researcher Arthur L. Schawlow theoretically prove that masers might be made to function in the optical and infrared regions and describe how this could be achieved in a joint study reported in Physical Review Letters. The optical maser is awarded a patent by Bell Labs to Townes and Arthur L. Schawlow afterward.

In 1960, the first laser is built by Theodore H. Maiman, a scientist at Hughes Research Laboratories in Malibu, California, using a cylinder of synthetic ruby. Trion Instruments, PerkinElmer, and Spectra-Physics are among the businesses that sell lasers on the commercial market.

In 1961, American Optical Society built and operate the initial optical fiber. A ruby laser from American Optical is used to eliminate a retinal tumor in the first medical use of a laser on a human patient.

In 1962, Hellwarth verifies his laser theory with Fred J. McClung, utilizing electrically switched Kerr cell shutters to generate peak powers 100 times that of typical ruby lasers. Q-switching is the name given to the process of producing huge pulses. Welding of watch springs is one of the first and most important uses.

In 1964, Noble prize in physics won by Townes, Nicolay Gennadiyevich Basov and Aleksandr Mikjailovich
Prokhorov for making oscillators and amplifiers based on laser and quantum electronics.

In 1966, "For the invention and improvement of optical techniques for investigating Hertzian resonances in atoms," Alfred Kastler receives the Nobel Prize in Physics.

In 1969, by the Laser Industry Association, the first colorful holographic image has been formed.

In 1970, after the decade, researchers studied the use of photonic principles in applications ranging from imaging to communications, establishing photonics as a different technology. And then science researchers of Bell Labs made the first CW laser in room temperature.

In 1972, Danis Gabor won the Nobel Prize for discovery of holographic method. On the other hand, Bell labs used laser to form electronic circuit patterns.

In 1973, a French physicist used the photon in the place of electron. The term “La Photonique” was used by him.

In 1977, in the case of optical communications, a very promising technology has been started moving forward revolution of the telecommunications field.

In 1980, National laboratories of US developed the telecommunication for better-quality coupling by using optical-spectra and the double heterostructure light-emitting diode (1330 nm). In the other hand, Charles Hard Town won award from Optical Society of America.

In 1981, Nicolaas Bloembergen, Arthur Leonard won Nobel in physics for developing the laser spectroscopy.

In 1882, with a unique production method, Norsk LCD A/S of Norway claims to be able to create LCD cells up to 30 × 30 cm.

In 1986, Ernst Ruska won Noble prize for working in electron optics and invented electron microscope.

In 1990, a total number of 3178 companies started the photonics related work like, Japan, India, Australia, South America and Israel.

In 1991, the argon laser pumped, erbium-doped fiber amplifier (EDFA), started using.

In 1994, Jerome Faist, Federico Capasso, Deborah L. Sivco, Carlo Sirtori, Albert L. Hutchinson, and Alfred Y. Cho created the prototype quantum cascade laser (QCL) at Bell Labs.

In 1997, The Air Force of the United States of America has approved an anti-ballistic Airborne Laser system. The 747-based system was built by TRW and Lockheed Martin.

In 1998, Steven Chu won Nobel Prize for developing the method of cooling and trapping atoms with laser light.

In 2003, first ever laser-powered aircraft is successfully flown by a group of researchers from NASA’s Marshall Space Flight Center in Edwards, Calif., and the University of Alabama in Huntsville.

In 2004, Ozdal Boyraz and Bahram Jalali of UCLA show electronic switching in a Raman laser for the first time. The first silicon Raman laser has a peak output power of 2.5 watts and works at ambient temperature. The pure-silicon Raman laser can be directly tuned to transfer data.

In 2005, John L. and Thedor W. won Nobel Prize for developing laser-based spectroscopy and the frequency comb technique.

In 2006, John Bowers and his team have been successfully built the electronically powered hybrid laser using cheap silicon industrial process.

In 2009, Charles Kuen Kao won Nobel Prize for successfully transmitting data through optical fiber. In the other hand, NASA established the Lunar Orbiter Laser Altimeter for assembling the 3D map information.

In 2010, Sandia National Laboratories researchers successfully formed a photonic integrated circuit by combining a terahertz quantum cascade laser and a diode mixer into a monolithic solid-state transceiver.

In 2012, the 192-beam laser system at the National Ignition Facility (NIF) delivered a record-breaking 500 TW of peak power and 1.85 MJ of UV laser light to its target.

In 2013, NASA’s Curiosity Rover had settled on Mars in May and used a high-powered laser to assess their composition by early December.

In 2014, researchers of MIT developed a photovoltaic system, which converts sunlight to electric energy with efficiency of 3.2 percent. In the other hand, European space agency has been started the laser communication between earth and satellite.

In 2015, the researchers presented a random Raman laser capable of creating a wide-field, speckle-free picture with a strobe time of less than a nanosecond at CLEO 2015. The random Raman laser pulse spanned a few nanoseconds and had a spectral width of around 0.1 nm, according to testing.

In 2016, in the March edition of Nature Photonics, researchers from Cardiff University, University College London, and the University of Sheffield announced that they produced quantum dot lasers on silicon which were electrically driven and emitted at 1300 nm.

In 2017, NASA improved the space communication with laser operation. On the other hand, laser weapons have been introduced to the US military.

In 2018, the laser system at the National Ignition Facility has established a new record by shooting 2.15 MJ of energy into its target chamber. This is a 15% increase above the NIF design standard of 1.8 MJ, and more than 10% greater than the prior benchmark.

In 2019, researchers used laser to make vibration and transmit the encrypted audio signal by a microphone.
This way laser and photonics technology became a major technology through the whole world, magnifying all the research ways.

After many failed attempts scientists got the idea to take down the temperature to the room level because at high temperature, photons cannot get coupled with the other sustainable materials, and again started the research and established the fiber optics and lasers [4, 5, 7]. All the optical communication technology was far away in the initial days of 2000s until the optical switching technology got developed and became reasonable. So by the twenty-first century, photonics ideas have been come out on the point of removing electronics with revolutionary science of telecommunications and networking technology. There were many workshops that took place for get together of photonics researchers in the early 1990s. In 1994, the Laser and Electro-Optics Society (LEOS, recently known as Photonics society) and Microwave Theory and Techniques society (MTT) started a global periodical meeting known as “International Topical Meeting on Microwave Photonics” [11–13].

Maybe the electrons are more flexible than photons, because by applying simple voltage, we can operate them toward the exact direction, but in the unavailability of any charges, the electrons are difficult to control as per the direction. The absence of voltage causes random diffraction and scattering of the electrons. By comparison, it can be said that when a photon is traveling long distance, the transmission is very easy, simpler, faster and much efficient than electrons transmission. Sometimes, at the time of turning on, photons may face some difficulty, so it is then converted into electrons before the turning on point. Scientists are working hard to overcome this disadvantage by squeezing the wavelength as tight as possible because it slows down the transmission. The dense wavelength-division multiplexing (DWDM) is the technique used by the scientist to squeeze the wavelength [2, 14]. Still there is a limit on how many light wave a single fiber can support. So electron conversions are seem to be necessary until the photonics switch as an optimum clarification. In the near future, scientists are thinking about the photonics crystals which can transmit data through light in straight lines as well as in all the bending corners with minimum distortion and with much bandwidth availability. This will become the gateway to open many other technologies. In the future, we might be able to see three-dimensional pictures by video calling through internet with flawless clarity. By using the traditional electronics RF radar systems as a remote sensing device to detect far afield target, in all weather conditions has been very crucial those days. In spite of so many hard works and efforts, RF radars still have some parameter limitations, which can be solved by the photonics radar [15, 16]. Scientists have always aimed for light weight and a miniature version of radar which can be used in self-directed vehicles, different types of navigation devices, aerial vehicles with very low power consumption and good resolution. Even, when some scientists used the monolithic microwave integrated circuit (MMIC), whose operation frequency is up to 300 GHz, it seemed unsatisfactory for small target radar imaging because the resolution limitation was 10 cm [17, 18]. But in photonics radar systems, a broadband signal generator and a receiver can be kept in one chip, and the resolution of 2.7 cm with an error less than 2.75 mm can be achieved.

Advanced Studies: Till this date, we are having the source and detection of microwave signals separately, which means transmitter and receiver devices are separately spaced. But most recently, the combined device studies have been started with a fully digitized system; this is called as PhoDIR, the first photonic digital radar [19, 20]. The Photonic Network National Laboratory (LNRF) and The Institute of Communication, Information and Perception (TECIP) collaborated and had a trial test of PhoDIR radar successfully. This PhoDIR system has an outstanding factor of having ten times reduced noise, which is comparatively improved than existing electronics technology. The photonics transceiver creates microwave signal through a single tunable pulsed laser, and after hitting the target, reverberation comes which is received by the photonics-based receiver. This radar works in real time, and the working frequencies of the signals depend on the photodiode band.

**RF generation and modulation**

For the generation of RF signals, ultra-high-speed digital electronics data are needed. We could achieve the frequency up to Giga Hertz with the traditional electronics radar systems, whereas with the photonics radar, we can meet the demand for higher frequency flexibility and wide bandwidth for the detection and generation of the enormously stable RF signals with arbitrary waveforms [21, 22]. In the process of RF generation, the signal of better sensitivity, better resolution, high adaptability, configurability and lower phase noise has been needed for the modulation technique. Many researchers have been done based on array antenna elements with RF phase delays, including the photonic filtering process. The phase stability of the RF signals decreases when the frequency multiplication takes place in high-frequency modulation. So, to improve this situation, two or more transmitters are used, which are very costly and power expendable. Switch-control loops and sweeping lasers with tunable media are also recent areas of research interest [23]. New-generation RADAR researchers have efficiently used photonics technology for the generation of high-frequency RF carriers with lower phase noise. The frequencies that lie within 30–300 GHz band can generate high-quality signals with low phase noise by photonics techniques. Till date, the lowest error rate \(10^{-11}\) of high-speed
data transmission has been achieved. There are various photonics techniques for RF signal generation from which we can get different ranges of frequency bandwidth, frequency tuning as well as stability. There are several techniques of modulation available, such as the heterodyning technique, external modulation technique, direct modulated laser technique and mode-locking technique. The basic RF generating equipments are electro-optic Mach–Zehnder modulator, multiplexer, optical amplifier and high-speed photodiode.

Heterodyning technique: This (optical heterodyning/photonixing) is the simplest technique to generate the microwave photonics signal. For this technique, a dual-wave source, an optical combiner and a photomixer are necessary [24]. Difference measured ($\Delta \lambda = \lambda_1 - \lambda_2$) between the two wavelengths gives the required electrical beat frequency. The required frequency can be obtained by controlling the optical frequency difference between the two lasers. As the wide wavelength tuning is possible, this technique is used in high data rate wireless communication. Another approach with the recompenses of thermal tuning is available, by which the range from 0 to 2750 GHz can be established [22]. But the main problem here is, uncorrelated noise in every feedback and that’s why the frequency of the beat signal is unstable. Let $A_1, A_2$ be the amplitudes, $f_1, f_2$ be the signal frequencies, and $\theta_1(t), \theta_2(t)$ be the phases of respective lasers [25, 26].

$$E_1(t) = A_1 \exp[j2\Pi f_1 t + j\theta_1(t)] \tag{3}$$

$$E_2(t) = A_2 \exp[j2\Pi f_2 t + j\theta_2(t)] \tag{4}$$

These are the output of two lasers. And after coupling of both the signals, the output will be:

$$E(t) = \frac{A_1[I(t) + jQ(t)] \exp[j2\Pi f_1(t) + j\theta_1(t)] + jA_2 \exp[j2\Pi f_2(t) + j\theta_2(t)]}{\sqrt{2}} \tag{5}$$

Here, $I + jQ$ is the modulated function. The block diagram of optical heterodyning RF generation process is shown in Fig. 1.

Directly modulated laser (DML): In this modulation scheme, microwave signals overlap or superimpose with the bias voltage of the laser and modulate them with the light signal [27]. Then, transmitted signal converts into the electrical signal by photodiode detection and passes through the filtering process to filter out the unnecessary frequencies [28]. This technique is very low cost and simple, but it is disadvantageous in terms of low bandwidth. Moreover, the current change will affect the refractive index and resonant wavelength, for which the modulation act degrades [29, 30]. This scheme is not suitable for high-frequency data transmission. The block diagram of optical external modulation RF generation process by DML is shown in Fig. 2.

External modulation: To overcome the stability problem and to improve data transmission, external modulation of microwave photonics generation is used. A high-speed intensity modulator, a phase modulator and an electrical absorption modulator are needed for this technique. In this technique, a highly stable signal passes through the Mach–Zehnder modulator with very minimum bias voltage and modulates at 50% of desired frequency. Here, the double sideband suppressed carrier modulation takes place.
and generates two optical sidebands of desired frequency difference ($f_0$). Using optical frequency comb generator, the harmonics of the modulation frequency can be generated. External modulator uses a laser light source and an external modulator to generate the microwave having light band. This technique employs multiple modulator combination to increase the bandwidth for carrying sufficient information. The characteristics of MZM can be written in the equation as
\[
E(t) = E_{in}(t) \cdot \cos(\Delta \theta(t)) \cdot \exp(j \cdot \Delta \theta(t))
\]
where $\Delta \theta$ is the phase difference information. The block diagram of optical external modulation RF generation process by external modulation is shown in Fig. 3.

Mode locking: This is another scheme of RF generation where a free-running laser, a PIN diode, an amplifier, and a frequency separator/discriminator are needed. From the laser source, a narrow linewidth comb is generated, which acts like an optical pulse. In the heterodyning modulation process, the laser beams are modulated and sum-up the effects, and the optical frequency comb has been generated along with, ultra-short femtosecond laser pulses. And the laser cavity length fixed the pulse repetition frequency and the frequency spacing [31]. The mode locking laser has two parts, such as gain section and saturation absorber section. Another structure of mode locking is called symmetric pulse code mode locking, in which two pulses propagate simultaneously. It has been verified that the mode lock laser (MLL) is able to do wide band modulation by generating frequency up to 300 GHz. For photonics RF signal generation, opto-electronics devices are very useful but also with limited tunability. In this situation, heterodyning of lasers is advantageous because it can produce any range of frequency of receiver band width and easily long-range transmission can be done. Multi-carrier frequencies can be generated by the MLL so that RF signals can be modulated with frequency flexibility. In RF domain, the side band filtering process is much easier after photodiode receiver, as it fixed the center frequency as desired frequency [32]. According to Fangzheng Zhang, 10–40 GHz has been achieved by using coded signals from direct digital synthesizers deprived of degrading the phase stability of MLL. In fact, MLL can replace electronics oscillator circuits to generate preferred RF signals, and it is able to eliminate the range ambiguity. Because of their inherent phase locking, MLL can select two laser modes, and by detuning, they generate high-frequency RF signal. One out of two mode is modulated by Mach–Zehnder modulator (MZM), another mode is for frequency shifting. In the method of generation of multiple RF signals, the different optical spectrum has to be formed by different intermediate frequency modulation techniques [29–31]. After generation of optical spectrum, they are fed to the antenna array through the optical fibers to produce phase delay. Next, the signals of each antenna element get paired up by tunable multiple band-pass filters and sent to photodiode. This is how the RF signals are generated. Photonics-based RF signal processing has plenty of real-time application in radar communication system. By changing the delay value, we can intentionally scan the optical beam. Though this technique has negligible propagation loss than the fiber transmission, still there is a disadvantage of this technique, i.e., the noise figure of non-linear transfer function. According to Janusz Murakowski, Garrett j. Schneider and Shouyuan shi, up-conversion of RF in photonics domain has been proven interesting development over electronics systems in the field of radar imaging. In this up-conversion, optical fibers are used only to pass the modulated optical beam from antenna to free space [33]. In Fig. 4, the block diagram of RF generation by mode locking is shown.

The spectral resolution and angular resolution are dependent on lengths of the optical fibers and the size of antenna array. According to Xingyuan Xu and Jiayang Wu, optical frequency comb is an alternative and advantageous solution of decreasing complexity due to laser arrays. In this case, the electro-optics and Fabry–Perot modulators are needed for high-frequency RF generation. So, advanced photonic RF signal processing achieved the integrated micro-ring resonator (MRR) optical frequency comb source with high-quality

![Fig. 3 RF generation by external modulation process](image-url)
factor (Q-factor) and high bandwidth. By feeding specific code, very good angular resolution and wide-ranging beam scanning can be achieved [23, 34, 35]. Photonics analog-to-digital converter takes the modulated signal from MZM and sends it to the photodiode, and then it tries to reconstruct the actual transmitted information. The test result of the scientists named Paolo Ghelfi, Francesco Laghezza and Filippo Scotti shows by putting a phase shift of 188 MHz. Photonics RF generator’s phase noise curve is 100th times at 40,000 MHz, i.e., lifted up by 40 dB as compared to the simple laser frequency. The new photonics integration technique can improve the RF generation act by producing different intermediate frequencies using DDS. For the beam scanning, increment in resolution purpose, phase modulation can be added to the DDS at the time of signal modulation [36–38].

Microwave-Photonic radar system architecture

The microwave photonics, RF generation and modulation scheme/technique mentioned above section should be continued by photonics-based radar system architecture. Photonics-based transceiver architecture having specific topographies and benefits. The photonics microwave radar architecture has mainly three parts, such as Tx/Rx module, optical components module and the signal processing module. Based on the optical module, the architecture can be divided into two types, such as opto-electronic hybrid structure and fully optical structure.

Opto-electronic hybrid architecture

It is very well-suited to the current radar system because it is the only traditional radar system with small optical subsystem. Therefore, it is well-acceptable by the radar researchers. But in this architecture, we need more than one optical to electrical (OE) and electrical to optical (EO) conversion which increases significant loss and noise; accordingly, the performance degrades. Opto-electronics hybrid structure was first demonstrated in the year of 1990s, for the optical beamforming networks. In 1991, HRL lab demonstrated the dual-band phased array-based optical beamforming network radar. In 1996, the 20° scan of phased antenna array was recognized by FSO modulators. Later, this hybrid radar structure was used in the wide band and very high-resolution applications of radar imaging, especially in SAR and ISAR [39]. This architecture results the fine resolution than the traditional beam scanning. Most recently, higher resolution can be achieved by this hybrid architecture with the dechirp processing of linear frequency-modulated (LFM) signal. Researchers are further improving this technology, such as dual-band LFMCW and full polarimetric radar. The block diagram of the opto-electronic hybrid architecture is given in Fig. 5.

The fully optical radar architecture

This includes the MLL to build the photonics-based transmitter receiver and RF generation methods. The mode lock laser can be called as the heart of this architecture. In this method, ultra-short optical pulse train is generated in the transmitter side for RF signal generation and on the receiver side, and the echo of the comb pulse processing is fixed. The reference pulse signal is also sent by the MLL. As the EO and OE conversion are summarized in this architecture, the
loss and noise is less, accordingly performance is improved. In the transmitter, two band-pass filters are there to select the required comb line. One comb line is being modulated, and another comb line is used for frequency shifting. After detection by the photodetector (PD), the radar waveforms get generated, and by changing the frequency of the baseband signal, the radar waveforms can be modified. So, wide frequency tuning range can be achieved. In the receiver side, echo signal is down-converted by the serial to parallel conversion, so that, the feasibility of using low-speed ADC increases. Recently, the upgraded version of MLL has the three comb line for using in multi-function applications [40]. The more simplified version of the dual-band microwave photonics radar setup has a modulation scheme in each comb line, and in the receiver side, no electrical filter needed because the electrical signal of the desired frequency cannot interfere with the undesired signal. This kind of architecture is used in target tracking (both aerial and naval) and landslide monitoring. Dual-band architecture guarantees the coherence of the signals while using both frequencies simultaneously. The block diagram of the fully optical radar system architecture is given in Fig. 6.

Multi-function microwave photonic radar

This is used for multiple signal manipulations at a same time with several multiplexing methods provided by the photonics technology. This architecture is low in cost and having compact hardware structure. This architecture is mainly used for communication in the warfare. The down-conversion is done to the echo signals after coming by hitting the target in the S-band and C-band [41]. With the ASK modulation, multi-function transmitter works as a communication transmitter. With this radar system architecture, up to 1.8-cm resolution has been achieved with the communication data rate of 100 Mbit/s. This architecture has been proposed in the application of fast-frequency calculation and high image resolution. Radar–lidar integrated system also can be implemented with this system structure as well.

Distributed microwave photonics radar

This is a flexible and large synthetic aperture radar does not have any positioning accuracy problem or limited sensitivity, and it is not affected by ambiguity or false alarm. In this distributed radar network, architecture optical fiber is used as the medium of signal transmission because of the low loss, delicate weight, electromagnetic interference immune and bidirectional transmission abilities. There is a central controlling system in this network to perform orthogonal LFM signal generation, processing and synchronization. Till now, the SNR gain of 8.333 dB is achieved, by which now the detection is 2.6 times better.

These are the all types of microwave photonics radar architecture. All the architectures are used in different application-based systems. The structure of main modulator is given below.

MZM

According to the Fresnel equation, we can find a law of light reflection, which is when light wave reflects off from low refractive medium-to-high refractive medium, it experiences a phase shift while passing through a dielectric medium. Mach–Zehnder modulator has an input waveguide which is split up into two waveguide interferometer arms, and then they are combined and again become single waveguides. It is the nonlinear medium present in the path that allows the electrical field to linearly vary optical fields. There is mainly two types of Mach–Zehnder modulator: single drive and dual drive; the basic principle is the same for both the modulators [42]. The dielectric coating-based beamsplitter helps to introduce that phase shift. Figure 7 shows the working principle of MZM.

The Mach–Zehnder modulator or interferometer is a device with two beamsplitters, which divides the light beam into two parts by the first beamsplitter and rejoins them by the second beamsplitter and focuses the reflected beam toward some direction [43]. There are two detectors present at the end of the interferometer. It depends on the path length and interference toward which detector the photons are going to fall. In the beginning of transmission, photon has zero phase shift, but till the time they reach the second beamsplitter by gaining a phase shift equal to the distance of the path divided by the wavelength, multiplied by two. One of the two paths experiences constructive interference and the other path experiences destructive interference. If the distance of both paths is equal in magnitude, then both

![Fig. 6 Fully optical photonic radar architecture](image-url)
the split beam will gain same phase. If the input optical field is equally split,  

\[ E_{\text{out}} = E_{\text{in}} \cos \left( \frac{\pi \ V}{2 \ V_{\pi}} \right) \]  

(7)

If the input optical field is not split between upper and lower arms  

\[ E_{\text{out}} = E_{\text{in}} \left\{ \cos \left( \frac{\pi \ V}{2 \ V_{\pi}} \right) - j \sin \left( \frac{\pi \ V}{2 \ V_{\pi}} \right) \right\} \]  

(8)

These beamsplitters are commonly made up of glass material with a metal or dielectric coating outside. Depending on the type of coating material, the light gets reflected from 50%–100% and remains transmitted. According to the design of K.P. Zetie, S.F. Adams and R.M. Tocknell, amplitude division interferometer has two different kinds of reflection to create change in the refractive index [44, 45]. There is various photonics-based applications where we need the Mach–Zehnder interferometer to introduce phase shift.

DPMZM

Nowadays, optical and electronics industries have joined together to form a new world of microwaves and photonics. There are different kinds of modulators available in photonics world, such as phase modulator (PM), polarization modulator (PolM), and intensity modulator (IM) to realize opto-electronics function. All the other phase controlling micro-electro-mechanical techniques available in the market, such as active vector modulator or variable resonant circuit, cannot support the high bandwidth application and also they have limited resolution, whereas photonics phase controller is a fantastic solution of this problem, even it has many advantages also. Photonic phase controller has better antenna feeding with no electromagnetic interference and very good isolation. For the purpose of inventing more complex structure realization method, scientists use the integrated version of two or more types of modulators together. As, two intensity modulators and one phased modulator are combined together to form dual-parallel Mach–Zehnder modulator (DPMZM). Most recently, a dual-phased quadrature phase shift keying modulator was also invented for several microwave photonics applications [46, 47]. In Fig. 8, DPMZM block diagram is shown.

In this modulator design with two DPMZM, one 90° rotator is kept together to increase the coordination steadiness. DPMZM is fed by an arbitrary electrical signal, which is divided into two parts and applied to two electrodes with equal amplitude and equal time. The bias points of both the electrodes and the modulator are maintained by DC power supply [48–50]. At the output, two phase controlling optical switches and two optical attenuators are placed. We need dual-phase shift controller because even a single-phase shift controller has a bandwidth limitation. In recent days, DPMZM is a multipurpose device that can create phase shifts for beamforming as well as it modulates the RF signals with phase tuning capabilities.

Transportation

The radar device has been extensively used for a huge bandwidth complex signal transmission process. The steadiness, consistency and reliability of the transmitted signal can be realized and also enhanced by signal processing method. The whole transmission process includes signal generation, amplification, detection and response. In this section, the different process of optical signal transportation has been discussed. The characteristics and method of transportation through single-mode fiber and multi-mode fiber are discussed.
SMF, MMF and PMF

For communication of the optical signal, the fiber optic cable has a big role. It has three kinds of coating like, the cladding layer over the glass core, primary coating layer and the protective glass layer [51]. One of the properties of optical fiber is, it has high refractive index. There are two types of optical fiber cable, such as single-mode fiber cable and multi-mode fiber cable. If the diameter of the glass core of the fiber is more than the wavelength of the light source, then we need the multi-mode fiber-optical transmission. In the long-range transmission, there is high chance of side mode dispersion, which reduces the transmission scope of the multi-mode fiber. So, multi-mode optical fiber cable is only suitable for the short distance and low-speed transmission [52]. It has low attenuation, high bandwidth and excellent anti-bending performance using for Gigabit Ethernet. Now, if the diameter of the glass core of the fiber is same as the wavelength of the light source, optical fiber works only in single mode or basic mode and avoids the higher order modes. As the side dispersion does not happen in single-mode optical fiber communication, it is used for long-range communication [53]. One special type of single-mode optical fiber is the polarization maintaining optical fiber. Only linearly polarized light can pass/propagate through the fiber cable. These types of optical fiber used in those applications where the polarization needs to be preserved. There is no cross-coupling taking place in between two modes [54].

Radar is a platform for fiber optics. In the phased array radar, a large bandwidth between antenna array and data acquisition system is present. In this place, fiber optics cable works very efficiently with a big amount of information transformer. These fiber optics also use in processors and FPGA boards. Radar used in land vehicles, air vehicles and water vehicles, which wants a large bandwidth system, fiber optics cable use in those applications.

Power divider

For this purpose, optical switches and different types of modulators and connectors are used. Single-mode fiber-to-fiber coupling can be finished by linear grooving. Single-mode fiber-to-waveguide coupling can be done by silicon finishing. These are the entire optical power transfer techniques. Partial power coupling is also needed. At a naval research laboratory, in Washington, sir S.K. Sheem successfully fabricated a single-mode optical fiber power divider by etching with HF/NH_{4}F solution. Total four ports are there in the power divider, where two ports are used for optical fiber inputs, and another two are for filling and draining. Optical fiber power splitter works similar as coaxial cable transmission system only; it divides a light beam into multiple streams. It can be same or in some other ratio.

\[
\text{PR} = \frac{P_t}{P_i} \times 100
\]

\[
\text{IL} = -10 \times \log \left( \frac{\text{SR}}{100} \right) + \Gamma_1
\]

where splitter insertion loss is IL, \(P_t\) is the optical output power for a single port, \(P_i\) is the total optical power output, SR is the splitting ratio and \(\Gamma_1\) excess loss of the splitter. The most applications of the power divider are like in passive optical networks. In an article on photonics, Retno Wigajiatri Purnamaningsih stated a power divider based on mode coupling using GaN/Al_{2}O_{3}. In this photonics generation for achieving more speed in the optical communication domain, by the optical power divider, integrated circuit has been designed with the Wilkinson power divider method. It is a three-port network, one port is for input and another two ports are for output. The output ports are matched to avoid losses. In this system, 55.4% of the input power has been coupled [55].

Wavelength-division multiplexing

One of the major topics for the optical transportation system is the wavelength-division multiplexing technique or WDM [56]. In this scheme, one multiplexer and a demultiplexer are required. By combining the different wavelengths of laser light, it transmits the information data for communication purposes. At the adjacent transmitter side, various signal wavelengths combine together at the multiplexer, and at the side of the receiver, the demultiplexer splits them apart into different signals. This merging and splitting phenomena are done by prism-like optical device. This was invented in the year of 1978, and first implemented in 1980 [57]. With the help of EDFA or erbium-doped fiber amplifier, the configuration of the wavelength-division multiplexing can be decided. In the television-cable application, the WDM is used for upstream and downstream signals [58]. It permits many different wavelength signals to share one optical path or fiber cable. If the interference happens inside, the cross-talk will appear, then we have to recover the RF signal. The main advantage of WDM is, the dissimilar frequency can be transferred over the same optical fiber channel, which increases the transmission capacity over in reduced cost [59, 60]. One of the core applications of WDM is a synchronous optical network. WDM can accommodate 80 channels over 4 THz. One 2D wavelength demultiplexer can accommodate 1000 channels in C-band with the help of phased array radar [61]. Figure 9 Shows the WDM.
Erbium-doped fiber amplifier (EDFA)

This fiber amplifier is very important for fiber-optical communication over high range. It amplifies the wavelength of that frequency range where the fibers get minimum loss. EDFA is made up of rare-earth-doped fiber [62]. It can pump the laser by the stimulated emission. WDM is a very important aspect in underwater optical communication for increasing the capacity of transmission. As the result of the underwater experiments, capacity up to 100 Gb/s has been reported yet. The amplifier design for WDM transmission is very important as it needs the band regularity [63]. Also it gives a satisfactory performance for all the networks which are necessary for WDM. For equalizing all the channels, pass-band equalizer filter can be used which is made up of fiber gratings. In the long distance transmission cases, the power of the amplifier should be limited to avoid the optical nonlinear elements. Using this EDFA technology, eight-channel WDM 352-km transmission over 10 Gb/s has been demonstrated by AT&T. It is shown that no concatenation is required for the EDFA system, so no need for band shaper also [64]. The optical transmission is to be done greatly by the WDM along with the EDFA, and it is also an increasing demand for worldwide telecommunication [65, 66]. The EDFA block diagram in shown in Fig. 10.

New exemplar is set in technology related to radio, due to the hybridization between the microwave and photonics systems, increased performance and implementation in the new fields with greater help in the communication systems and also for the safety for public [67, 68]. Specifically, in the systems of radar, the usage of photonics has led to multifunctional systems of a present-day generation which can easily take care of various synchronous coherent signals of radio at various frequencies, which helped in carrying out modern surveillance by validating multispectral imaging [69, 70]. The flexibility demand in the software-defined radar architecture is easily matched by photonics due to large and maintainable bandwidth. It has also led to making a compact system by the help of single shared transceiver which can be used for multiband operations with the additional capability of integration of photonic. In Table 1, a comparative data study between photonics radar and electronic radar has been done and shown.

Concept of radar transportation based on photonic system

We can get effectual transmission data result from the radars which are working in the millimeter bands with very wide-spread bandwidth. Transmission of electromagnetic rays through optical frequencies is advantageous over microwave rays signal propagation. For the optical range transmission, we need networks which are having high modulation frequencies and high data rate. These are the successful remedies and moderately easy job for our communication requirements [71]. For the implementation purpose, we need efficient optical sources such as mode-locked lasers (MLL), optical signal modulators such as optical fiber, electro-optical modulators, high speed photodetectors like metal–semiconductor-metal (MSM) diodes, optical phase shifters and beam dividers [72, 73]. Photonic radar is very modern radar, used nowadays as a substituting idea for all radar using in electronics technologies. Its photonics system transforms the electrical field into electromagnetic signals and so as the opposite.
Optical detection and RF conversion

Traditional RF radars need several down-conversions to fit the bandwidth with the ADC in the receiver side, and this process adds amplitude and phase noise. To convert the light signal to electrical signal, we need optical detectors [74]. Afterward, the electrical signals are being enlarged and controlled. The types of commercially off-the-shelf photodetectors are photomultipliers tubes, vacuum tubes, semiconductor photodiodes and phototransistors [75]. Phototransistors are nothing but photodiodes with internal amplifying circuits. These are much more comfortable for being small size with the optical fiber cables. The basic principle of these detectors is the energy of the incident light release as photons [76]. If light bandwidth is bigger than the band gap of the material, then electron–hole pairs are generated. Once the circuit gets power supply, the photocurrent is generated and starts flowing to the outer circuit

$$\Lambda = \frac{hc}{E_g} = \frac{1.24}{E_g(eV)}$$

(11)

where $\lambda$ is the absorption wavelength, $E_g$ is the band gap, $h$ and $c$ are Plank’s constant and speed of light, respectively. In the semiconductor materials, after absorbing, the energy of electron goes to the conduction band. If the bias voltage is applied, the electrons start flowing, and the current flow starts in the external circuit [77]. The current is reverse bias, i.e., due to the minority carrier, the current flows in the opposite direction. The photodiode operation follows the equation:

$$I_d = I_{do}(e^{qV_d/2kT} - 1) + I_p$$

(12)

where $I_d$ is the device current, $I_p$ is the photocurrent, $I_{do}$ is the dark current, $q$ is the charge of the electron, and $V_d$ is the junction voltage and temperature $T$ is in kelvin. Photodiode is able to transform electrical energy from the light energy, which is called quantum efficiency ($\eta$). Suppose $e$ denotes the no. of carriers per second and $p$ denotes no of incident photons per second; then,

$$\text{Quantum efficiency} \eta = \frac{e}{p} \text{s}$$

(13)

$$R_j = \frac{I_p}{P}$$

(14)

where responsivity $R_j$ depends on the ratio of radiant energy to incident energy, usually measured in A/W. These photon detectors can be further classified into three groups like, photoconductive detector, photovoltaic detector and photoemissive detector [78]. In the photoconductive, the conductivity of the semiconductor material changes when the light falls on it and then it starts to function. In the photovoltaic detectors, a junction is present between the region of electron and the region of hole. The device is activated with a voltage generation while light falls on it. In the photoemissive detector, photoelectric effect works. The incident photons activate the external circuit after releasing the electrons. In photodiode light detector, when light is incident on the diode, the reverse current starts flowing. The sensitivity depends on the wavelength of light. But the phototransistor current flow depends upon the intensity of the incident light. In Table 2, different photodetector characteristics are listed.

### Microwave photonic filtering

In the receiver system, after the photon detection, filtering process is very essential. Due to filtering the whole received signal can be noise-free, spurs-free and interference-free. Modern digital signal processing has given many types of filters to this generation. But still, the RF

| Parameter                   | Photonics-based transceiver | Electronics-based transceiver |
|-----------------------------|------------------------------|------------------------------|
| Transmitter                 |                              |                              |
| Frequency band of carrier signal | Flexible up to 40 GHz       | > 2 GHz                      |
| SNR                         | > 73 dB/MHz                  | > 80 dB/MHz                  |
| IF                          | 200 MHz, can be extend with MLL | < 2 GHz                      |
| Receiver                    |                              |                              |
| Input carrier frequency     | Flexible up to 40 GHz        | < 2 GHz                      |
| Spurious-free dynamic range | 50 dB                        | > 70 dB                      |
| Sampling jitter             | < 10 fs, integrated in [10 kHz–10 MHz] | > 100 fs, integrated in [10 kHz–10 MHz] |
| Effective number of bits    | 7 for up to 40 GHz           | 8 for > 2 GHz                |
broadband radar cannot use the analog filters to their front end because of the inadequate dynamic range ADC. The electronics filters are able to realize the insertion loss, passband flatness, edge sharpness and band rejection very accurately [79]. But there comes the limitation of repro-grammable and reconfigurable of these electronic filters. As usual, photonics-based radars have achieved massive electro-optical bandwidth, it is preferred to convert the RF signals to optical signal so that the analog-to-digital conversion may get easy [80–82]. Paolo Ghelfi and Francesco Laghezza told about the time lens approach, where optical signal is anticipated to stretch in the time domain to make sampling process easier. The multiband and multifunctional software-defined radar use for high speed switching. Here, in this microwave photonics radar system, the microwave photonic filtering can be used [83]. This filtering process does not induce any EO and OE conversion loss. In the optical domain, we can get the advantage of introducing delay to the low loss and lightweight optical fiber in the photonics filtering process. With different optical multiplexing techniques, optical devices allow outstanding multichanneling filtering with the help of microwave photonic filtering [84]. These optical devices are well consistent and have high bandwidth. In the process of microwave photonic filtering, the signals are divided and sent to a finite impulse response filter (FIR) and infinite impulse response filter (IIR) accordingly. After the photodetection, positive half coefficient of the incoming signal can be easily realized, but for the negative half, we have to introduce 180° phase shift. For achieving the tuning between the microwave photonic filtering without distressing the shape of the frequency response of the signal, the complex coefficient of the filter should be introduced. There are several methods for obtaining the complex coefficient like, stimulated Brillouin scattering, fiber Bragg grating, linearly spaced delay, liquid crystal silicon, etc., but these methods have limitations of narrow bandwidth [85].

Getting the full spectral range is very difficult using 360° phase shift. That is why the complex coefficient has been introduced by the polarization modulator. A full 360° phase shifter was made with the help of the polarization modulator and the polarization controllers. By controlling the controllers, the frequency can be tuned without changing the response shape. 3 dB bandwidth can be easily acquired by changing the simultaneous polarization controllers and time delays. In Fig. 11, the block diagram of microwave photonic filtering is shown.

Till date, a single pass-band microwave filter and fiber ring resonator has been realized and the Q-factor obtained 1.7 × 10^4, 3 dB bandwidth obtained is 825 ± 125 kHz and center frequency obtained 2–16 GHz. In current times, microwave photonic filters come as a compact device having low cost and less power intake [86].

![Fig. 11 Microwave photonic filtering](image-url)
Optical beamforming

Another name for phased array antenna is directive antenna, which is made of more than one radiating element and help us to create radiation pattern in any direction of detection by introducing the relative phase delay to each antenna element [87]. In initial 1990, the work of beamforming introduced true time delay (TTD) [61]. This phase array application is versatile in both the army and commercial sectors. There are two types of array antenna patterns available in market, such as regular arrays and irregular arrays [88]. To the receiver side, each antenna element is connected with ADC to form the digital beam. That beam can be steered to any angle between 0 to 180 degree by introducing phase delays with necessary software coding. This is called as digital beamforming [89]. Mainly two types of beamforming are there, conventional or fixed beamforming and adaptive beamforming. In conventional beam forming, a fixed set of weights get multiplied by the incoming signal. The time delays get added with the array elements initially and then the signal processing is done. But in conventional beamforming, we are not able to cancelled all the interference, whereas adaptive beamforming interference signal gets canceled, because at the time of signal processing, a null vector has to be put in the direction of interference. Adaptive beamforming multiplies the weights according to the signal preference and combines the information. MUSIC, SMI, RLS, and MLE are the adaptive beamforming algorithms. Due to non-linearity of phase shift in each antenna element, distortion in digital RF beamforming arose. Moreover, this wide band RF beamforming needs hundreds of terahertz of signal processing rate, which is impossible even in the most advanced digitized system. In Fig. 12, block diagram of optical beamforming scheme is shown.

According to US Army Research laboratory, photonics-based radar systems can take over this kind of disadvantage [90]. Radio frequency-based photonic radar produces optical beamforming by introducing true time delay in each antenna element [91, 92]. The recent momentous progress has been made by setting up RF to RF link with low-cost execution and great spurious free dynamic range (SFDR). The different number of beam scanning positions depends on the number of beam splitters, numbers of gratings and tunable laser source. Thus, the generation of whole system seemed to be very complex and costly. So, ARL designed a simplified, integrated photonic system on chip-scale and usable in UAV systems. ARL first designed a free space optics (FSO)-based TTD generator with linear transposition mechanics. One right-angled mirror worked as beam splitter which can duplicate the time delay the number of time equal to sensor element number. The Chebyshev filter has been used for realization and interference reduction. After this experiment, they had applied the fiber optics based system. Finally, the latest applications are based on photonics system. There are several advantages of photonics-based phased array radar over the electronically scanned array radar, like, the processing of radio frequency and microwave frequency can be controlled with light weight, smaller size elements. Even this photonics-based system is immune to electromagnetic interference (EMI) with lower loss [93]. These all are necessary to get squint free beam. Sometimes because of temperature and stress little error signal can be produced by the system internal wired connections. As a summary, it can be said that true time delay unit, high power and low noise amplifier, RF attenuators, transmitter and receiver system and photonics switches; these all are the crucial instruments for designing a beamforming architecture. A brand new silicon photonics device, named Hydex, has been able to create a delays of 2 nano-second. This is cost effective, CMOS compatible, compressed with high yield manufacturing, can be integrated on a chip. Instead of using silicon-based photodetector, the hybrid of silicon and germanium (Si-Ge) has been used for photodetector as a receiver due to a slighter band gap [93, 94].

Fig. 12 Optical beamforming scheme
Photonic analog to digital conversion

As the photonics application in coming generation is growing very fast and better, the high-performance ADC is also essential for the high-speed DSP modules. So, we need ADC which is having high sampling rate [95]. Optical heterodyning using MLL, RF signal down-conversion can be done in any frequency to find information. The intermediate frequency can be generated by detuning the RF side bands with the nearest MLL comb and pass through ADC. The sampling rate is equal to optical pulse repetition rate. This is the method of RF high-frequency sampling with the help of photonics. In the newest technology of photonics, used in ADC having analog sampler and for very less timing jitters [96]. The pulses produced by the MLL and the timing jitter (i.e., delta dirac) signals are the best sampled signals. These samples are modulated by the analog signals and verified by the peak intensity values. After the photodetector converts the optical pulses to the electrical pulses and ADC makes it quantized and matched. The photonics sampling method is able to manage large pulse duration analog signals. A limitation of photonics sampling, instantaneous bandwidth is a problem in overcoming that sampling rate of multiple ADC. In a project, using three dual-port MZM, the samples can be divided into four similar channels. In Fig. 13, photonics sampling is shown.

Another type of photonics ADC has the capability of preprocessing the analog signal due to which, the signal gets stretched in the time domain and it slowed down. MLL-generated short pulse is first pre-chirped and then modulated with the input analog signal. The waveform of the analog input gets mapped on the pre-chirped signal. Then, again the pulse gets chirped along with the analog signal which results in the time stretching [97]. This stretched sample detected by the PD is very much easier to realize for further processing. Since the signal is slowed down in the time domain, noise generated by the timing jitter can be easily removed. Improvement of this research of the ADC is still in progress. Till now, a microwave photonic based ADC with 5 stretch factor has been demonstrated in X-band [98].

Photonic radar transceiver

In modern era, scientists do not use separate modules for transmitting and receiving for radio communication purposes, instead they invented one unique module which can able to transmit and receive data [99]. From walkie-talkies to modern cell phones, all are examples of transceiver. Here, we have explained about the photonics-based RF transceiver which help the technology to reduce the size, cost and complexity. As transmitter MLL generates the RF signals, the output gets modulated by an electro-optical modulator. After that, the optical signal is being detected by the photodiode and creates a duplicate waveform to transmit the information [100]. In Fig. 14, the block diagram of photonics-based transceiver system is shown.

At the receiver that same MLL receives the signal and is detected by a low bandwidth photodiode and is down-converted it. Thus, we get the original signal back. This prototype may help the future generation wireless communication [101, 102]. After getting success in single band (X-band)
photonics radar testing, the dual-band photonics radar is also got successful. In a field testing of GEM elettronica of San Benedetto Del Tronto, Italy, the detection is done by the PhoDIR. The echo from the moving boat placed at a 0.43 nmi distance has been detected successfully [103].

**Microwave photonics for measurement application**

Radar can be called as a significant measurement system in the world of microwave. After transmitting the electromagnetic signal and getting back the echo signal from the target, radar can analyze and measure the parameters like, position, velocity, range, resolution, image under radiation area, characteristics of target etc. Two types of parameter measurements are there; one is of power, phase and frequency related measurement type and another is of position, velocity and angle of arrival related measurements type [104]. Here, we discussed about electric field measurement, microwave spectrum analysis, instantaneous frequency measurement, wavelength-division multiplexing, time division multiplexing, microwave Doppler frequency shift measurement, angle of arrival measurement, phase noise measurement and GPS positioning.

**Microwave spectrum analysis**

Optical spectrum analysis based on wavelength scanning is a very good measurement technique. The OSA or optical spectrum analyzer used for spectrum measurement of a wide range frequency. Usually, photonics-based microwave spectrum analysis can be classified into two types, one is spectrum measurement through optical channelizer, and another one is spectrum measurement through spatial spectral material. In the method of optical channelizer, RF signals first get transformed in optical signal via electro-optical modulator (EOM) and then it has been divided into parallel channels. Each channel having different frequency, distributed with different angles can be detected by photodiode (PD) and sent for further signal processing. The optical channelizer is the main key component of spectrum measurement. In the method of optical spatial spectral material, an earth-doped material is made and applied to realize the broad band frequency spectrum [105]. Here, the hole burning effect of the material has been analyzed. Two monochromatic beams from the laser engrave the absorption by the hole burning effect. Then, the RF is transformed into the optical signal, detected by photodetector and sent for the further signal processing. Till now, with the help of Fabry–Perot, spectrum analysis of frequency range of 40 GHz the resolution of 90 MHz has been achieved. Lately, chip-based photonic Brillouin filter is used in photonic frequency scanning receiver. In Fig. 15 the block diagram of microwave spectrum analyzer has been shown.

**Instantaneous frequency (IF) measurements**

All the frequency scanning methods mentioned above have limitation on measuring the instantaneous frequency. Starting from electronic warfare to various applications, the instantaneous frequency measurements or IFM is very important part. Recently, the IFM is calculated by mapping the frequency information to optical or electronic power, by which IFM can be understood very easily and quickly. This mapping method can be done with the help of either optical comb filter, optical mixer or delay element. In the measurement based on the optical comb filter, the frequency gets transformed to optical power by the mapping method. Thus, the IF frequency can be measured [106]. MZM is used to create two different frequency carrier signals with the suppressed carrier double sideband modulation process. Similarly, two optical powers needed to be detected by the PD. Then, the calculated power ratio is the microwave frequency measurement. For the frequency range 1–20 GHz, measured error is less than 200 MHz. Instead of using one laser source, a complementary optical comb filter coupler can be used for the same realization. The power ratio is as

![Fig. 15 Microwave spectrum analyzer](image)
where $F$ is the free spectral range of the comb filter and the $f_m$ is the instantaneous frequency of the microwave signal. Now, based on measurement of the optical mixing unit, a mixer is created between optically modulated signal and the microwave signal with a time delay, which gives a shifted version of output power. A microwave signal is correspondingly split into two halves and feed to the MZM. Then, the IFM is calculated by the detection by PD. To increase the frequency measurement range, a small delay can be added to the optical link to get rid of the distortion in the coaxial cable. Another method of measurement based on dispersive element used the dispersive delay to familiarize the microwave power fading for designing photonic-based microwave filter. As both are frequency-dependent, the IFM can be done by the microwave power detection [107]. To make the IFM independent of microwave power, more than two power ratios are needed to be derived. If two powers can be detected by two channels, the ratio will be

$$R = \frac{1 - r \cos \left( 2\pi f_m / F \right)}{1 + r \cos \left( 2\pi f_m / F \right)}$$  \hspace{1cm} (15)$$

where $c$ is the velocity of light in space, $\lambda_1$ and $\lambda_2$ are the wavelengths of both channels, $R_1$ and $R_2$ are the power losses in the link, $x_1$ and $x_2$ are the chromatic dispersion of both channels, $\alpha$ and $\beta$ are the phase shifts. In the electronics intelligence system and defense system, the instantaneous frequency measurement is very important. The aforesaid methods are used for detection of a single frequency. But in warfare systems, there are more than one frequency detected by the receiver. So it is highly desirable to measure multiple IF [108]. The multiple frequency measurement based on frequency to time mapping is the solution to measure multiple IFM. IFM block diagram is shown in Fig. 16.

**Doppler frequency measurement**

With all the above discussions of photonics-based technologies, advance research photonics-based measurement systems are now cable to measure the Doppler frequency approximation and passive direction finding with multi-antenna-based GPS positioning system.

Recently, photonics-based electro-optical mixing technologies have been proposed to measure Doppler frequency shift (DFS) in different domains, like advanced mobile communication, electronic-radar warfare, medical science, metrology, etc.[109]. Lately, to measure the Doppler frequency shift, two methods are proposed/developed, i.e., photonics mixing approach and the vector mixing approach. In the photonics mixing-based approach, Doppler frequency will shift because of the mixing between echo signals in optical domain. According to Xihua Zou, Bing Lu and Wei Pan, a proposal of two cascaded electromagnetic modulators is explained. Transmitted signal is applied to EOM1 to modulate the optical carrier. At the receiver side, received signal is applied to EOM2 for modulating the signal generated by EOM1. At the output, the low-frequency optical signals are produced and detected by the low-frequency photodiode as electrical signal. The new Doppler frequency is measured by the equation

$$F_D = \frac{(F_M - F_M')}{2}$$  \hspace{1cm} (17)$$

where $F_M$ and $F_M'$ are the transmitted and received signal frequencies, respectively. In this DFS measurement, it is clear that for the shift of $-90$ to $+90$ kHz, measurement error is less than $\pm 5 \times 10^{-10}$ Hz. In the optical vector mixing-based approach, the necessity of spotting the DFS and DOA (direction of arrival) can be meet. In this method, the optical mixing merges with the optical frequency offset. It has two routes, in one route the optical carrier is being upshifted, and in other route, the optical carrier is modulated by the echo signal. Then, the two routes get merged, coupled and

![Fig. 16 Instantaneous frequency measurement](image-url)
detected by the PD, further it generates the low-frequency signals. By adding or subtracting the low-frequency signal from the earlier upshifted frequency, we can get the DFS [110]. For measurement range of − 90 to + 90 kHz, measurement error comes less than ± 60 Hz. In this measurement scheme, a photonics hybrid vector mixing has been introduced. In that method, phase \([I(t)]\) and quadrature phase \([Q(t)]\) detection by photodetector have been engaged. The both outputs from the two balanced photodetectors are being calculated. By differentiating the phase relationship between \(I(t)\) and \(Q(t)\), we can determine the DFS value. For measurement range of − 90 to + 90 kHz, measurement error comes less than ± 5.8 Hz. The efficiency has been improved tremendously. In Fig. 17, block diagram of Doppler frequency measurement is shown.

**Angle of arrival measurement**

Angle of arrival measurement is a crucial parameter in the electronic warfare, mobile communication system, both civil as well as defense uses. Its measurement method is done to suppress the interference and increase the information signal power. By measuring time delay between the signal source and antenna element, angle of arrival can be determined. Photonics-based direction of arrival depends on the phase shift to power mapping method [111]. We can categorize the angle of arrival measurement method as, far field and near field. In case of far field, as the distance between target and antenna element is large, the microwave signal received by the antenna array is almost parallel to each other. So, by detecting the delays of the echo signal, we can find the AOA. Now introducing the photonics, it takes us one step ahead. Two cascaded electro-optical modulators and one microwave filter are used in this method. These modulators are biased at minimum bias point. By calculating the time delay between two modulators, we can get the AOA. The equation for AOA calculation is

\[
\theta = \cos^{-1} \left( \frac{\tau c}{d} \right)
\]

where \(\tau\) is the time difference of arrival, \(c\) is the speed of light in space, and \(d\) is the distance between two antennas. Here, \(\tau\) is proportional to \(d\).

In case of near-field approach, the distance between the target and antenna element is small. For location detection using photonics methods, a large band optical fiber is needed to connect different units with the central unit, where proper time delay between two respective units is known. In Fig. 18, the AOA block diagram is shown. With the help of power mapping or using geometric technique, target localization approximation can be done. The time difference of arrival (TDOA) detected at the antenna elements with various optical carriers explains a hyperbolic curve, by which we can measure the AOA. Many algorithms like MUSIC (multiple signal classification) and MLA (maximum likelihood algorithm) have been improved for estimating the accurate measurement values. Till now, 1° accuracy is achieved, while beam scanning range is from 300 kHz to 6 GHz [112–114].

![Doppler frequency measurement](image-url)
Photonics approach is adopted for many signal processing structures to perform time frequency analysis, such as Fourier transform, short-time Fourier transform, wavelet transform and Fourier cosine transform. First, the measurement and analysis of time and frequency of a microwave signal after sampling and shaping with the help of optical filter is done and then again transformed to frequency domain. In STFT, pulse shaping system with thin and linear chirp fiber Bragg grating is used to give time window and realize the Fourier transform [115]. In two-dimensional array, Mexican Hat wavelet transform has been executed. Fourier cosine transform is also a successful and popular algorithm for photonic time–frequency measurement.

**Phase noise measurement**

Phase noise measurement is absolutely necessary for making low-phase noise electronic design. By optical mixing of the optical signal and its self-introduced delayed signal, the phase noise can be removed. Photonics approach of measurement is having very high sensitivity including wideband. With the help of photonics processor, all electro-optical conversion, i.e., time delay and the phase control, can be managed. Till now, photonics-based phase noise measurement for 5–40 GHz frequency is calculated as 123 dBC/Hz at 1 kHz. The microwave photonics-based phase controller has a principle of introducing phase difference between RF side band and carrier signal at the receiver [116]. This principle has several drawbacks, like, higher budget and complicated structure to control also the slow tuning time is not appropriate for phased array antenna. So an integrated module has been discovered to overcome this disadvantage. DPMZM and optical phase shifter (OPS) are integrated together to permit both polarization with different optical phases to the side band carrier. Block diagram of phase noise controller is shown in Fig. 19.

The optical carrier signal beats the photodiode to create the RF signal with the same phase difference. This phase controller operation can take place in remote locations also, but as the polarization is very sensitive, we need to maintain a continuous connection or a stabilizer between optical source and DPMZM. Modern dual-polarization dual-parallel (DP-DPMZM) has been formed with two DPMZM, and each DPMZM is consists of two MZM. Total three bias ports are present in DP-DPMZM. One DPMZM has been fed by RF signal with both upper and lower sidebands. But the bias is set in such a way that, the output should have only the upper sideband and the lower sideband should be suppressed. DP-DPMZMs are now commercially available in the market also.

**Range resolution**

To get the range resolution of any radar, we can use the following formula as

\[ R_{res} = \frac{C}{2B} \]  

(19)

where \( C \) is the velocity of light traveling in free space, \( B \) is the bandwidth of the waveform. A microwave signal bandwidth of 1.5 GHz can give a resolution of 0.1 m in synthetic aperture radar (SAR) [117]. For a wide range of high-frequency bandwidth (suppose tens of GHz), transmitting, receiving and processing is impossible to be done in single electronic circuits. Even RF front end-based antenna does not give good outcomes. So, this generation got the photonics system to overcome all these situations with multi-function and multiband integration. Usually, for microwave radar measurements, electronics devices have very good resolution and suppleness is used. Nevertheless, high-speed, high-bandwidth microwave signal measurement will always need
modern photonics science. [118]. Photonics-based technique converts the broad band microwave signals to optical signals, which can drastically compress hundreds of terahertz frequency in optical domain. So, by using low power consumption and low cost optical devices, we can easily eliminate this problem. After all the processing and measurement, the electrical up-conversion is very easily done by optoelectrical oscillators. The flow of the microwave parameter measurement is like this, first, the microwave signal is converted into optical signal by electro-optic (EO) modulator then optical signal processing module measures all the parameters and converts them into amplitude function, after this a photodetector pulls out these data [119].

The block diagram of photonics radar parameter measurement is shown in Fig. 20. This technique can be used to measure the contactless parameters like position and velocity for high performance, high speed radar. Electric field measurements are specially done for the large metallic antennas, but metal distorts the actual measurement of electric field. But, the Pockel’s EO modulator can stop this distortion with dielectric inside it, even it helps to measure the transient electric field [120–123]. An optical amplitude modulator EO sensor has two numbers of polarizers, which are orthogonal to each other. When the electric field is applied to get measured, the refractive index of dielectric medium of EO crystal changes. Thus, the measurement takes place. In recent invention, photonics-based radar setup has been established with transceiver supporting 40 GHz broadband [124, 125].

Contemporary applications of photonics radar technology

In the twenty-first century, photonics science and engineering is making a major contribution in national defense sector. Photonics-based intelligence, surveillance and reconnaissance (known as ISR systems) is the next-generation invention. A photonics-based very wide-view-passive sensor has been developed concerning optical surveillance system. Photonics radar detection system is used in various fields like, aircraft, terrain, space craft, water vessels, guided missiles, motorized vehicles, etc.[126]. Due to this invention, a large area view is possible with high resolution even in the sun light environment. Slowly all our defense schemes like radar imaging, remote sensing, weapons and military communication are converting into optical based systems. Modern defense applications include definitude laser machining, optical semiconductor integrated circuits as in optical lithography, solar power for remote locations, etc. [127–129]. In Harnessing Light publication, we find the photonics-based defense mechanisms, such as night vision and surveillance, optics-based chemical and biological detection and optical processing. Laser diode effectiveness has made a good improvement in the available wavelengths of national defense system like aperture synthesis. In past, there was a time when a high power laser pointer was used as a laser dazzler against the enemy pilots to make them permanently blind. But from 1995, US government has banned permanent blindness. Now, the laser dazzlers are used to create temporary blindness to make the pilot and the aircraft confused.

Photonics radar in defense application

The optical sensors have made an excellent evolution in last decade in the ISR data performance, the area exposure has increased very much. The Defense Advanced Research Projects Agency (known as DARPA) is in the process of making more advanced materials which can diminish camouflage of target in three dimension. In the last decade, a huge amount of laser-based night vision equipment were commercially available, that too in very low cost. The laser diode efficiency has been increased and they help to minimize the probability of information blocking, jamming, interference and detect the target with minimal power consumption. One of the specific extension in military air force is MANPADS, i.e., Man Portable Air Defense System. According to Missile Defense Agency (MDA), they were successful to take a revolutionary step by destroying a boosting ballistic missile by airborne laser experimental setup. So, at very low cost as compared to the existing system, at a distance of almost thousands kilometers, various targets can be attacked at a speed of light [130]. Fiber optic systems got advanced in 1996 when photonics crystal fibers came in the field. Optical
signal processing is a very promising medium to perform complex mathematical functions, like 2D imagining at very fast speed. This is called as integrated opto-electronics [131]. A trial test of photonic radar, and the result shows that, from 0.42 nmi photonic radar was able to detect a movable boat on sea.

Several photonics data processing techniques are flourishing day by day, such as multi-mode laser sensing technology, Synthetic aperture laser radar, hyper spectral sensing and wide-angle surveillance sensor technology. In the long distance applications, high-resolution remote sensing and good valued cross-range resolution is a severe problem, which can be overcome by using synthetic aperture sensors [132]. Synthetic aperture radar systems are changing from RF-based system to advanced photonics-based system. The first laser imaging synthetic aperture radar is called Synthetic Aperture Imaging Ladar (SAIL). It is capable with 60 micron range resolution and 50 micron cross-range resolution. The first experiment of focusing on a moving target by SAIL was done in late nineteenth century by United Aircraft Research Laboratories. Afterward, Nd:YAG microchip laser based Inverse Synthetic Aperture Imaging Ladar (ISAIL) experiment was done for 2D imaging. Optical Synthetic Aperture radar (SAR) imaging is very interesting technology now a days. The main advantages of this technology are improved image acquisition, detection time and brightness of efficiency [133].

**Target detection**

One of the most popular radar applications in radar is target detection. While the range resolution of the photonic radar is far better than the conventional radar, so similarly the target detection accuracy is also high in the photonics radar compared to conventional radar. The use of several algorithms for radar signal processing is the same as we were using before in fully RF radar [134]. Slowly the signal processing is including the machine learning, deep learning, artificial intelligence, neural network etc. In the paper Zhang, Guo and Pan, they showed real-time high-resolution target detection by FMCW-photonic radar. They generated 8 GHz LFM signal by frequency quadrupling and using 500 MSa/s sampling rate, got the range resolution of 1.875 cm. There are so many target detection applications in military as well as civil applications [135]. The photonics radar is able to detect multiple target and their range, velocity and Doppler shift at a same time. Researchers are using time frequency analysis for the micro-Doppler signature detection of the low RCS targets. As low RCS targets are the recent threats of our warfare, we have to be more specific in these detection. FMCW-photonic radar is nowadays using for autonomous vehicles and surveillance system industries [136]. Short-time Fourier transform (STFT), wavelet transform (WT), Wigner–Ville distribution, Hilbert transformation (HT), etc., are the mostly used signal processing algorithms.

**Photonics radar for land slide monitoring**

To examine the boundaries of the landslide at the shallow and depth of geological situations is called the landslide monitoring. Dr. Filippo Scotti, and Suzanne Melo researched and proposed a technique to measure small displacement and detection of landslide. This technique can also be used for detecting the structure failure of constructions. Civil engineering department is mainly interested in inclination constancy monitoring applications. So every small and little displacement can be detected to prevent the structure failures [137]. Researchers used stepped frequency continuous wave signal modulation techniques for differential phase calculation. The accuracy of less than 0.2 mm for the distance up to 400 m has achieved.

**Photonics multi-antenna-based global positioning system (GPS)**

Previously, GPS had an error to calculate vertical and horizontal positioning for the satellite sky distribution. Now, photonics-based laser feedback system is generated for the satellite positioning system. After the signal is produced by the local oscillator, it is divided into two routes through optical fibers and one of them is sent to semiconductor amplifiers and another goes to the satellite station. Then, that GPS signal down-converted to the IF signal and returned back to the satellite station. Here, phase difference is measured between two incoming signals. This phase difference and the relative delay helps to measure accurate GPS position [138].

**LiDAR or light detection and ranging**

This technology uses laser light to measure the elevation of things like the ground, forest, and buildings etc. As the sonar uses sound waves for mapping things and radar uses radio waves, similarly lidar uses the light. There are three ways to collect data from lidar systems, like from ground, from airplane even from space satellites. The airborne lidar system is the most commonly used lidar system for collecting data. Now, we need to understand the four parts in the airborne LiDAR system. The first one is, the laser light from the transmitter scans the earth from above as the plane flies [139]. In the laser the ultraviolet range, visible range and the near-infrared range. The next one is, for finding latitude, longitude and altitude it needs GPS system, which allows to figure out where are the lidar reflection is on the ground. The third one is inertial measurement unit (IMU). This IMU tracks the tilt of the plane in the sky as it flies in the sky, which is important for accurate elevation calculations. And
the last one is data accusation system and a computer which helps to store or record the data collected by the lidar. The principle of lidar data collection is as follows. First, the laser of the lidar system scans the earth by actively emitting light energy toward the ground. A burst of light energy is admitted from the lidar system, which is known as pulse, and the reflected light energy what to be recorded is known as return. To get the altitude, lidar measures the time that takes for a light energy to travel to the ground and back. Suppose the total travel time is $T$ and speed of light is $c$, the multiplication we have to divide by 2 since the light traveled to the ground and back.

Distance = $\frac{T \times c}{2}$ \hspace{1cm} (20)

This calculation gives us how far the light actually traveled to ground and the distance between the plane and the ground.

In airborne LiDAR, helicopters and UAVs are used for data collection. This way LiDAR technology has the capability to deliver high-resolution and accurate detection and range, is a game-changer. LiDAR is being used in many application such as, in field if augmented reality, satellite in space, autonomous car driving, Internet of things and in artificial intelligence also. In recent studies of photonics, radar is being integrated with a LiDAR subsystem for range and detection purpose. In a paper of Zhongyang Xu, Jianing Zhao, Fangzheng Zhang, they worked on photonics Radar-FMCW LiDAR integrated system. A DPMZM modulator in the transmission part generates a carrier-suppressed dual-sideband (CS-DSB) optical signal. One part of optical signal from MZM is directly transmitted by lidar, whereas the radar signal is generated from the beat signals between the two optical sidebands of the CS-DSB optical signal. In the receiving part of the system reflected light signal gets de-chirped. Similarly, the radar signal is also gets de-chirped. They used a K-band photonics-based radar with an 8 GHz bandwidth and a 1550-nm FMCW lidar with a 4 GHz bandwidth are combined into a setup in this demonstration. For the radar and lidar subsystems, the standard deviations of displacements between observed and predicted distances are 0.342 and 0.997 cm, accordingly [140, 141].

**Photonics-hologram technique**

Nowadays, hologram technology has entered into to every sector, from doctor’s office to entertainment and even smart phone-based augmented reality. Holography is photonic photography technique that records scattering light and forms a three-dimensional image as an optical illusion. Recently at the human media laboratory in Queen’s University of Kingston started the holographic video conferencing method. In the field of entertainment, we can see the use of hologram in every sci-fi (science fiction) movie [142–144].

**Photo-thermal process to control cell activity**

The scientists of Washington University invented a technique to do reverse modulation of electrical activity in nerve cell and heart muscles with the help of nanoparticles as photo-thermal transducers. This is a great achievement for neuroscientist. Heat is generated by the nanoparticles after absorbing near-infrared light, and then nanoparticles transfer that heat to the neurons for participating electrical activity. Sir St. Loise and Srikanth Singaneni have discovered this method to control the neural activities [145].

**Thermal detection by photonics radar**

Thermal imaging or thermal detection is a method in which human eyes are able to see in the dark environment. There are several thermal cameras preset, which can detect the temperature of the objects around us. Nowadays, thermal target detection using radar system is very common work. This type of radar is called thermal radar [146]. One security camera is preset in the thermal radar system, which rotates 360° continuously. We can get up to 16 types of view with the thermal camera with a geospatial platform. One thermal radar can give a coverage of 200 acres. It is a very good security strategy for military applications [147]. Thermal radar is becoming the appropriate surveillance and identification option for crucial infrastructure areas as well as for organizations on their field of interest. The multi-sensor fusion thermal radar system has been presented by Chen-Chau Chu and J.K. Aggarwal, which is capable of sensing the thermal image segmentation as well as detection of targets. This multi-sensor includes laser as a photonic source. In adverse weather condition the conventional thermal radar system gives more interference that photonics thermal radar systems.

**Photonic-laser therapy in the medical field**

Doctors of this era have initiated a new medical treatment techniques like laser therapy. By tuning the laser light to some specific wavelength and power of photonic-laser, various medical issues such as shrink and destroy tumors, detecting cancer, removal of kidney stones, repairing retina, improvement eye vision and hair loss treatment can be cured [148].

**The present corona virus (SARS-CoV-2) crisis**

(COVID-19 pandemic) situation influences the photonics industry in several ways. There are some correlations coming between spreading of corona virus and laser action.
This is another photonic marketing. Medical experts and laser physicist are considering that photonics is having an important role in this crisis. Hope in future many photonics research will be on this topic [79, 149–151].

### Emerging quantum radar technology

Quantum radar achievement is the unique phenomenon of quantum mechanics. We need to know about three things regarding quantum radar, such as quantum system, quantum state and quantum entanglement [152, 153]. A quantum system is a system to performs quantum mechanics in space, based on wave particle duality. The time duration of performing quantum mechanics is called quantum state. In this quantum, state photon shows the duality property, i.e., half wave and half particle [154–161].

Quantum entanglement is the method of generating a pair of photon particles, both interact in same space and area. These two particle frequencies will be exact same, as if we cannot define two particles differently. For generation of quantum entanglement, a crystal or a quad crystal is required for passing the laser beam through it. After passing through the crystal, the laser light gets scattered into photons horizontally and vertically. The energy vibrations are same for all those photons. These photons are called entangled to each other [162–166].

To make quantum radar, four main components are needed. These are, a system which can convert a laser beam to photon (entanglement generator), transmitter, receiver and electro-opto-mechanical converter. In the mechanism of quantum radar, one photon is sent to quantum memory and other one is sent to the object. In object, the noise reduction scheme is done and we can get that impact on the target. After that photodetector receives and detects the photon. After that the signal goes through the electro-opto-mechanical converter and filter, matching should be done with the quantum memory of photon. Any missing information can be recovered by the quantum elimination method in quantum entanglement [168].

In Fig. 21, the block diagram of quantum radar is shown. Quantum radar has various advantages, i.e., (i) higher target detection technique, (ii) considerable detection probability, (iii) more resilient to jamming, (iv) improved detection to clatter, (v) short and large cross section detection.

Two most important techniques have been proposed for quantum radar or quantum sensor for detecting the targets of interest, these techniques are, interferometric quantum radar and quantum illumination. There are three types of quantum sensor or radar techniques have been identified. In type-1 un-entangled quantum state of light is sent toward the target. In type-2, classical state of light is sent toward the target. At last, in the type-3, the entangled quantum state of light is sent toward the transmitter [2].

#### Single-photon quantum radar

This is an example of type-1 quantum radar. Here, transmitter sends a single photon toward the target, which gets hit by the target surface and returns back to the receiver for detection purpose. In this type of quantum radar, target looks apparently bigger than the classical measurement [169–176].

#### Quantum LADAR

This is an example of type-2 quantum radar. LADAR stands for laser detection and ranging. This type of sensor works in visible and near visible region. It has the advantage of detection of small spatial information as it works in smaller wavelengths. On the other side, it has some disadvantages also, i.e., it is unable to penetrate fog, water particles and clouds, so its application is limited in a nearby area only [177].

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**Fig. 21** Block diagram of LiDAR technology
Entangled photon quantum radar

This is an example of type-3 quantum radar. Here, an entangled photon pair is formed and one of those photons is transmitted to the target and other photon is kept in the sensor system. The first photon gets hit by the target and returned back to the receiver. At that time, the correlation between two photon particles has been watched in the entangled state to upgrade the detection performance [178–180].

Interferometric quantum radar technology

We can represent a whole quantum radar system as an interferometer assuming the arms are as long as radar detection range. Considering a Mach–Zehnder modulator having two mirrors and two beam splitters, we can calculate the phase delay of one arm by estimating the intensity of the output beams. Measuring the number of non-entangled photon in the output beam, the phase delay can be estimated. This interferometric quantum radar technique is used for detecting super sensitivity [181].

Quantum illumination technique

This technique increases the sensitivity of photodetector even in very noisy atmosphere. This is also having similarities with single-photon sensor and entangled photon sensor discussed earlier. In a very lousy atmosphere, we assume that the target is illuminated, to find out and detect the target is the main challenge here. The entanglement of two photons enhances the sensitivity of the radar system which helps to detect the target in high noisy environment [182].

Transmitter

This is one of the main element of quantum radar, where the entangled photon is generated. The most famous technique for entanglement generation in the visible region is parametric down-conversion method using nonlinear crystals. Another technique is intra-band transition technique. Photon-assisted tunneling experiments shows that this photon transition takes place in microwave region. As a result we get single particle levels in a quantum dot. Using four array quantum dots, we are able to produce entanglement generation. Those four quantum dots are connected to the electron reservoirs and injected inside a microwave generator, as shown in Fig. 22.

Receiver

Recently, a sensing technique is proposed which can detect single photons also. The proposed metamaterial is designed to absorb microwave photons and can be used to perform single-shot photodetection. This photon detection design is used in the visible and near visible regions [183–186]. This system consists of three-layered photo-absorbing particles in any arbitrary position. These absorbers are used for detecting microwave photons from the initial stage to excited stage subsequently. In Fig. 23, photon detection technique is shown [187–193] (Fig. 24).

Conclusion

Photonics-based radar system is the auspicious technology of the near future generation for recognition and dispensation of high bandwidth signals. We have the spectral transparency of frequency operation delivered by optical components and also the advantages of low cost, small size, light
weight and low power consumption. Optical signals do not interfere with the other unwanted electromagnetic waves in the environment while transmitting and receiving. This is one of the other prestigious advantages of using photonics radar. In recent times, research results have their validation about the usefulness of exploiting photonics system in radar surveillance. With the next-generation technology of photonics, the world can experience high speed, high clarity of data transmission and create an exciting market. In the near future, as the photonics market gets develops, the electronics telecommunication systems can be replaced by photonics service. In photonics applications, smartphones can be replaced by the smart glasses, which help the military, medical, industrial and civil applications. The optics eye-tracking sensors are now based on photonics technology. These ideas have been applied to both virtual reality headsets and augmented reality glasses which superimpose digital data all over the future digital world. Rather than using optics for regular light, specially designed optical waveguides are used to modify it. The new technology lowers installation area to a sixth of its current size while significantly increasing the field of vision. The small head-up displays can be even be fitted into motorcycle and pilot helmets to display augmented reality data directly in the range of vision. Nowadays, the most of the telecommunication system uses the hybrid version of photonics and electronics, i.e., opto-electronics system, as photonics system has very great and expandable carrying capacity. The photonics radar field trial tests are also confirmed about the coherent multiband task, multi-function working capabilities and software-based reconfigurability.

Declarations

Conflict of interest We wish to submit a review article entitled “A Survey on Photonics Technologies for Radar Applications” for consideration by Photonic Sensors Journal. We confirm that this survey work is original and has not been published elsewhere, nor is it currently under consideration for publication elsewhere. We believe that this manuscript is appropriate for publication by Photonic Sensor. We have no conflicts of interest to disclose. Authors carried out the studies of photonics technology for radar application in details. The summary of photonics discovery timeline has been displayed from early days to modern days. All the available techniques of radio frequency generation, modulation, transportation, optical detection, conversion and measurements are summarized in this article. Also, different types of the photonics radar architecture and some important applications are discussed. At last, a brief description of quantum radar architecture and functionalities is written.

References

1. T. Borowski, M. Pasternak, J. Pietrasinski, The photonic radar: the situation today and the prospects for the future, in Radioelectronic Systems Conference (2020), p. 114420
2. P. Ghelfi, F. Laghezza, F. Scotti, G. Serafino, A. Capria, S. Pinna, D. Onori, C. Porzi, M. Scaffardi, A. Malacarne, V. Vercesi, E. Lazzeri, F. Berizzi, A. Bogoni, A fully photonics-based coherent radar system. Nature 507, 341 (2014)
3. C. F. Middleton, E. J. Grafer, J. R. DeSalvo, Photonic frequency converting transceiver and related methods, U.S. Patent 9,680,576, B1 (2017)
4. F. Agulló López, J.M. Cabrera, F. Agulló-Rueda, Electrooptics: Phenomena, Materials and Applications, 1st edn. (Academic Press, 1994), pp. 219–249
5. S. Li, Z. Cui, X. Ye, J. Feng, Y. Yang, Z. He, R. Cong, D. Zhu, F. Zhang, S. Pan, Chip-based photonic radar for high-resolution imaging, arXiv e-prints, 1905 (2019)
6. H. Kumawat, A. Bazil Raj, SP-WVD with Adaptive-Filter-Bank Supported RF Sensor for low RCS Targets’ Nonlinear Micro-Doppler Signature/Pattern Imaging System. Sensor. 22, 1186 (2022)
7. J. Murakowski, G.J. Schneider, C.A. Schuetz, D.W. Prather, Photonic probing of radio waves for k-space tomography. Opt. Express 25, 15746 (2017)
8. A. Bogoni, F. Berizzi, A. Capria, P. Ghelfi, F. Laghezza, E. Lazzeri, A. Malacarne, F. Scotti, D. Onori, S. Pinna, C. Porzi, M. Scaffardi, G. Serafino, V. Vercesi, PhoDIR photonics-based fully digital radar, in IEEE International Topical Meeting on Microwave Photonics (2013), p. 25
9. A. Kanno, K. Fukunaga, N. Yamamoto, T. Kawanishi, Photonics-based millimeter-wave radar system for handheld applications, in 2017 IEEE Conference on Antenna Measurements & Applications (CAMA) (2017), p. 334
10. I. Kassotakis, Modern radar techniques for air surveillance & defense. J. Comput. Model. 4, 189 (2014)
11. Modern Radars (Elsevier, 2001), https://www.sciencedirect.com/topics/engineering/modern-radar
12. Ground Radar Capabilities (Northrop Grumman), https://www.northropgrumman.com/Capabilities/GroundRadar%20Capabilities/Pages/default.aspx
13. V. Gorokhov, The historical development of radar science and technology as the prelude to the modern information revolution. Icon 12, 168 (2006)
14. Radar Systems (Wikipedia, 2021), https://en.wikipedia.org/wiki/Radar
15. M. L. Skolnik, Introduction to radar systems, 3rd edn. (McGraw-Hill, 1980)
16. S. Haykin, Cognitive radar: a way of the future. IEEE Signal Process. Mag. 23, 30 (2006)
17. V. Ravetti, Performance evaluations of frequency diversity radar system, in Proc. Eur. Microwave Conf. (2007), p. 1715
18. J. B. Tsui, Digital Techniques for Wideband Receivers, 2nd edn. (SciTech, 2004)
19. J.A. Scheer, Coherent radar performance estimation, in IEEE International Conference on Radar (1993), p. 125
20. M.A. Richards, J.A. Scheer, W.A. Holm, Principle of Modern Radar: Basic Principles (SciTech Publishing, 2010)
21. S. Horiguchi, K. Arakawa, Y.Minamikata, T. Nagatsuma, Error-free 30–50 Gbps wireless transmission at 300 GHz, in The Asia-Pacific Microwave Conf., (2013), p. F3E-3
22. A. Deninger, A. Roggenbuck, S. Schindler, S. Preu, 2.75 THz tuning with a single-DFB laser system at 1550 nm and InGaAs photomixers. J. Infrared Millim Terahertz Waves 36, 269 (2015)
23. A. Karar, M. Yañez, Y. Jiang, J. Cartledge, J. Harley, K. Roberts, Electronic dispersion pre-compensation for 10709-Gb/s using a look-up table and a directly modulated laser. Opt. Express 19, B81 (2011)
24. T. Nagatsuma, A. Hirata, N. Shimizu, H. J. Song, N. Kukutsu, Photonic generation of millimeter and terahertz waves and its applications, in Proc. 19th Int. Conf. Appl. Electromagn. Commun. (2007), p. 1
25. K. Balakier, M. Fice, L. Ponnampalam, A. Seeds, C. Renaud, Monolithically integrated optical phase lock loop for microwave photonics. J. Lightw. Technol. 32, 3893 (2014)
26. Y. Yoshimizu, S. Hisatake, S. Kuwano, J. Terada, N. Yoshimoto, T. Nagatsuma, Generation of coherent sub-terahertz carrier with phase stabilization for wireless communications. J. Commun. Netw. 15, 569 (2013)
27. K. Williams, M. Thompson, I. White, Long-wavelength monolithic mode-locked diode lasers. New J. Phys. 11, 1 (2014)
28. D. Yanson, M. Street, S. McDougall, I. Thayne, J. Marsh, E. Avrutin, Ultrafast harmonic mode locking of monolithic compound cavity laser diodes incorporating photonic bandgap reflectors. IEEE J. Quantum Electron. 38, 1 (2002)
29. S. Arariba, Y. Matsui, Y. Ogawa, Mode-locking at very high repetition rates more than terahertz in passively mode-locked distributed-Bragg-reflector laser diodes. IEEE J. Quantum Electron. 32, 1211 (1996)
30. J. Parker, A. Sivananthan, M. Lu, L. Johansson, L. Coldren, Integrated phase-locked multi-THz comb for broadband offset locking, in Optical Fiber Communication Conference (2012), p. OMM3E-5
31. M. Inoue, M. Hodono, S. Horiguchi, K. Arakawa, M. Fujita, T. Nagatsuma, Ultra-broadband terahertz receivers using polymer substrate. IEEE Trans. Terahertz Sci. Technol. 4, 225 (2014)
32. S. Beer, H. Gulen, M. Pauli, C. Rusch, G. Kunkel, T. Zwick, 122-GHz chip-to-antenna wire bond interconnect with high repeatability, in Proc. IEEE Int. Microw. Symp. (2012), vol 1
33. N.H. Zhu, Z. Shi, Z.K. Zhang, Directly modulated semiconductor lasers. IEEE J. Sel. Top. Quantum Electron. 24, 1 (2018)
34. M. Alhalabi, F. El-Nahal, N. Taspinar, Comparison of different modulation techniques for optical OFDM intensity modulation and direct detection IM/DD system, in Proceedings of the 2019 IEEE 7th Palestinian International Conference on Electrical and Computer Engineering (PICECE) (2019), p. 1
35. C.R.S. Fludger, J.E.A. Whiteaway, P.J. Anslow, Electronic equalisation for low cost 10 Gbit/s directly modulated systems, in Proceedings of the Optical Fiber Communication Conference (2004)
36. A.L. Balan, N.D. Alexandru, Inter-symbol interference free pulses for transmission over intensity-modulated channels, in Proceedings of the 2014 10th International Conference on Communications (COMM) (2014), p. 1
37. A. Khilo, Photonic ADC: overcoming the bottleneck of electronic jitter. Opt. Express 13, 4454 (2012)
38. J. Chou, J.A. Conway, G.A. Sefler, G.C. Valley, B. Jalali, Photonic bandwidth compression front end for digital oscilloscopes. J. Lightw. Technol 27, 5073 (2009)
39. F. Laghezza, Jitter-limited photonic analog-to-digital converter with 7 effective bits for wideband radar applications, in Proc. IEEE Radar Conf. (2013), p. 1
40. A. Bogoni, P. Gelffi, F. Laghezza, F. Scotti, G. Serafino, S. Pinna, PHODIR: Phonetics-based fully digital radar system, in 2013 IEEE International Topical Meeting on Microwave Photonics (MWP) (2013), p. 25
41. P. Gelffi, F. Scotti, A.T. Nguyen, G. Serafino, A. Bogoni, Novel architecture for a photonics-assisted radar transceiver based on a single mode-locking laser. IEEE Photonics Technol. Lett. 23, 639 (2011)
42. P. Gelffi, F. Laghezza, F. Scotti, D. Onori, A. Bogoni, Photonics for radars operating on multiple coherent bands. J. Lightw. Technol. 34, 2 (2016)
43. F. Zhang, S. Pan, Microwave photonics signal generation for radar application, in 2016 IEEE International Workshop on Electromagnetics: Application and Studet Innovation Competition (iWEM) (2016), p. 1
44. P. Gelffi, F. Laghezza, F. Scotti, G. Serafino, S. Pinna, A. Bogoni, Photonic generation and independent steering of multiple RF signals for software defined radars. Opt. Express 21, 22905 (2013)
45. S. Chin, L. Thevenaz, J. Sancho, S. Sales, J. Capmany, P. Berger, J. Bourderionnet, D. Dolfi, Broadband true time delay for microwave signal processing, using slow light based on stimulated Brillouin scattering in optical fibers. Opt. Express 18, 22599 (2010)
46. K.Y. Song, M.G. Herraez, L. Thevenaz, Observation of pulse delaying and advancement in optical fibers using stimulated Brillouin scattering. Opt. Express 13, 82 (2005)
47. P.A. Morton, J.B. Khurgin, Microwave photonic delay line with separate tuning of the optical carrier. IEEE Photonics Tech. Lett. 21, 1686 (2009)
48. O.F. Yilmaz, L. Yaron, S. Khaleghi, M.R. Chitgarha, M. Tur, A. Willner, True time delays using conversion/dispersion with flat magnitude response for wideband analog RF signals. Opt. Express 20, 8219 (2012)
49. J. Mork, R. Kjaer, M. van der Poel, K. Yvind, Slow light in a semiconductor waveguide at gigahertz frequencies. Opt. Express 13, 8136 (2005)
50. H. Su, P. Kondratko, S.L. Chuang, Variable optical delay using population oscillation and four-wave-mixing in semiconductor optical amplifiers. Opt. Express 14, 4800 (2006)
51. J.J. Zhang, J.P. Yao, photonic true-time delay beamforming using a switch-controlled wavelength-dependent recirculating loop. J. Lightw. Technol. 34, 3923 (2016)
52. A. Kanno, K. Fukunaga, N. Yamamoto, T. Kawanishi, Photonics-based millimeter-wave radar system for handheld applications, in Proceedings Of 2017 IEEE Cama (2017)
53. J. Murakowski, G.J. Schneider, S. Shi, C.A. Schuetz, D.W. Prather, Photonic probing of radio waves for k-space tomography. Opt. Soc. Am. 14, 15746 (2017)
54. Z. Tegegne, C. Decroze, P.D. Bin, T. Fromenteze, C. Berthele, Single channel microwave photonics digital beamforming radar imaging system. J. Lightw. Technol. 36, 3 (2018)
55. W. Zhou, M. Stead, S. Weiss, O. Okusaga, L. Jiang, S. Anderson, Z.R. Huang, Developing an integrated photonic system with a simple beamforming architecture for phased-array antennas. Appl. Opt. 56, B5 (2016)
56. R.J. Mailloux, Phased Array Antenna Handbook (Artech House, 2005)
57. M. Zatman, Digitization requirements for digital radar arrays, in Proceedings of the 2001 IEEE Radar Conference, 01CH37200 (2001), p. 163
58. M. Mitchell, J. Fraschilla, Digital beamforming subarray architecture for naviy digital array radar (DAR), in presented at the 48th Annual Tri-Service Radar Symposium, Monterrey, vol. 56 (2002), p. B5
59. S. Garakoui, E. Klumperink, B. Nauta, F. Vliet, Phased array antennas. Appl. Opt.
60. W. Ng, A. Walston, G. Tangonan, J. Lee, I. Newberg, J. Bernson, Z.R. Huang, Developing an integrated photonic system with a simple beamforming architecture for phased-array antennas. IEEE Photonics Tech. Lett. 19, 1529 (2007)
61. R. Ghosh, J. Shmulovich, C. Kane, M. Barros, G. Nykolak, A. McPherson, A polarization beam splitter. Adv. Opt. Mater. 6, 17005852 (2018)
62. J. Federici, B. Schulkin, F. Huang, D. Gary, R. Barat, F. Oliveira, D. Zimdars, THz imaging and sensing for security applications- explosive weapons and Drugs. Semicond. Sci. Technol. 20, S266 (2005)
63. D. Cook, B. Decker, G. Maislin, M.G. Allen, Through container THz sensing: application for explosive screening. Terahertz Gigahertz Electron Photonics III 5354, 55 (2004)
64. W. Lee, S. Nirantar, D. Headland, M. Bhaskaran, S. Sriram, C. Fumeaux, W. Whyachumankul, Broadband terahertz circular-polarization beam splitter. Adv. Opt. Mater. 6, 17005852 (2018)
65. M. Yamaguchi, F. Miyamaru, K. Yamamoto, M. Tani, M. Hangyo, Terahertz absorption spectra of L-, D-, and DL-alanine and their application to determination of enantiometric composition. Appl. Opt. 46, 53903 (2005)
A. True, K. Schroeck, T. French, C. Schmuttenmaer, Terahertz spectroscopy of histidine enantiomers and polymorphs. J Infra-red, Millim Abd Terahertz 32, 691 (2011)

C. Reid, E. Pickwell-MacPherson, J. Laufer, A. Gibson, J. Heden, V. Wallace, Accuracy and resolution of THz reflection spectroscopy for medical imaging. Phys. Med. Biol. 55, 4825 (2010)

A. Luukanen, R. Appleby, M. Kemp, N. Salmon, Terahertz Spectrosc. Imaging 491 (2013)

J. Jackson, J. Bowen, G. Walker, J. Labaune, G. Mourou, M. Menu, K. Fukunaga, A survey of terahertz applications in cultural heritage conservation science and technology. IEEE Trans. Terahertz Sci. Technol. 1, 220 (2011)

G. Walker, J. Bowen, W. Matthews, S. Roychowdhury, J. Labaune, G. Mourou, M. Menu, I. Hodder, J.B. Jackson, Sub-surface terahertz imaging through uneven surfaces: visualizing Neolithic wall paintings in Çatalhöyük. Opt. Express 21, 8126 (2013)

D. Fitzgerald, E. Berry, N. Zinov’ev, S. Homer-Vanniasinkam, R. Miles, J. Chamberlain, M. Smith, Catalogue of human tissue optical properties at terahertz frequencies. J. Biol. Phys. 29, 123 (2003)

D.M. Mittleman, R.H. Jacobsen, M.C. Nuss, T-ray imaging. Infrared, Millimeter, Terahertz Waves 36, 318 (2015)

K. Zetie, S. Adams, R. Tocknell, How does a Mach-Zehnder interferometer work? Teach. Phys. 35, 46 (2000)

O. Morozov, I. Nureev, A. Sakhabutdinov, A. Kuznetsov, G. Morozov, G. Il’in, S. Papazyan, A. Ivanov, R. Ponomarev, Ultra-high-resolution optical vector analyzers. Photonics 7, 14 (2020)

Z. Tang, S. Pan, J. Yao, A high resolution optical vector network analyzer based on a wideband and wavelength-tunable optical single-sideband modulator. Opt. Express 20, 6555 (2012)

M. Xue, S. Pan, Influence of Unwanted First-Order Sideband on Optical Vector Analysis Based on Optical Single-Sideband Modulation. J. Lightw. Technol. 35, 2580 (2017)

R. Hernández, A. Loayssa, D. Benito, Optical vector network analysis based on single-sideband modulation. Opt. Eng. 43, 2418 (2004)

J. Román, M. Frankel, R. Esman, Spectral characterization of fiber gratings with high resolution. Opt. Lett. 23, 939 (1998)

M. Xue, Y. Zhao, X. Gu, S. Pan, Performance analysis of optical vector analyzer based on optical single-sideband modulation. J. Opt. Soc. Am. B 30, 928 (2013)

M. Xue, S. Pan, X. Gu, Y.J. Zhao, Optical single-sideband modulation based on a dual-drive MZM and a 120-degree hybrid coupler. J. Lightw. Technol. 32, 3317 (2014)

W. Li, W. Sun, W. Wang, L. Wang, J. Liu, N. Zhu, Reduction of measurement error of optical vector network analyzer based on DPMZM. IEEE Photon. Technol. Lett. 26, 866 (2014)

M. Xue, S. Pan, Y. Zhao, Accuracy improvement of optical vector network analyzer based on single-sideband modulation. Opt. Lett. 39, 3595 (2014)

M. Xue, S. Pan, Y. Zhao, Accurate optical vector network analyzer based on optical single-sideband modulation and balanced photodetection. Opt. Lett. 40, 569 (2015)

S. Li, M. Xue, T. Qing, C. Yu, L. Wu, S. Pan, Ultrafast and ultra-high-resolution optical vector analysis using linearly frequency-modulated waveform and dechirp processing. Opt. Lett. 44, 3322 (2019)

M. Xue, W. Chen, B. Zhu, S. Pan, Ultrahigh-resolution optical vector analysis for arbitrary responses using low-frequency detection. IEEE Photon. Technol. Lett. 30, 1523 (2018)

M. Xue, W. Chen, Y. Heng, T. Qing, S. Pan, Ultrahigh-resolution optical vector analysis using fixed low-frequency electrical phase-magnitude detection. Opt. Lett. 43, 3041 (2018)

Z. Tang, S. Pan, A high-resolution optical vector network analyzer with the capability of measuring bandpass devices, in Proceedings of the IEEE International Topical Meeting on Microwave Photonics (MWP) (2013), p. 225

M. Xue, S. Pan, Y. Zhao, Large dynamic range optical vector analyzer based on optical single-sideband modulation and Hilbert transform. Appl. Phys. A 122, 197 (2016)

M. Xue, S. Pan, C. He, R. Guo, Y. Zhao, Wideband optical vector network analyzer based on optical single-sideband modulation and optical frequency comb. Opt. Lett. 38, 4900 (2013)

M. Wang, J. Yao, Optical vector network analyzer based on unbalanced double-sideband modulation. IEEE Photonics Technol. Lett. 25, 753 (2013)

J. Román, M. Frankel, R. Esman, Spectral characterization of fiber gratings with high resolution. Opt. Lett. 23, 939 (1998)
140. Z. Xu, J. Zhao, F. Zhang, L. Zhang, Photonics based radar lidar integrated system for multi sensor fusion application. IEEE Trans. Sensor J. 20, 15068 (2020)

141. F. Zhang, P. Du, Q. Liu, M. Gong, X. Fu, Adaptive strategy for CPPM Single-photon collision avoidance LIDAR against dynamic cross-talk. Opt. Express 11, 12237 (2017)

142. X. Xue, X. Zheng, H. Zhang, B. Zhou, Tunable 360° photonic radio frequency phase controller based on optical quadrature double-sideband modulation and differential detection. Opt. Lett. 36, 4641 (2011)

143. L. Anderson, B. McMurtry, High speed photodetectors. Proc. IEEE 54, 1335 (1966)

144. H. Melchior, M. Fisher, F. Abrams, Photodetectors for optical communication systems. Proc. IEEE 58, 1466 (1970)

145. J. Conradi, P.P. Webb, Silicon reach-through avalanche photodiodes for fiber optic applications, in Proc. 1st Eur. Conf. Optical Fiber Communication, London, vol. 22 (1995), p. 128

146. M. Pan, Y. Haung, Q. Li, H. Luo, H. Zhi, S. Kaur, M. Qiu, Multiband middle infrared compatible cemoflage with thermal management via simple photonic structures. Nano Energy 69, 104449 (2020)

147. S. Pirandola, B. Bardhan, T. Gehring, C. Weedbrook, S. Lloyd, Advances in photonic quantum sensing. Nat. Photonics 12, 724 (2018)

148. J. Campbell, Recent advances in telecommunications avalanche photodiodes. J. Lightw. Technol. 25, 109 (2007)

149. G. Foschini, R. Gitlin, J. Salz, Optimal direct detection for digital fiber optic communication systems. Bell Syst. Tech. J. 54, 1389 (1975)

150. J. Capmany, J. Mora, I. Gasulla, J. Sancho, J. Lloret, S. Sales, Microwave photonic signal processing. J. Lightw. Technol. 31, 571 (2013)

151. M. Fok, J. Ge, Tunable multiband microwave photonic filters. MDPI Photonics 4, 45 (2017)

152. T. Zhang, H. Zeng, R. Chen, Simulation of quantum radar target cross section for electrically large targets with GPU. IEEE Access. 7, 154260 (2019)

153. F. Zeng, J. Wang, J. Yao, All-optical microwave bandpass filter with negative coefficients based on a phase modulator and linearly chirped fiber Bragg gratings. Opt. Lett. 30, 2203 (2005)

154. Y. Dai, J. Yao, Nonuniformly-spaced photonicmicrowave delay-line filter. Opt. Express 16, 4713 (2008)

155. X. Yi, T. Huang, R. Minasian, Tunable and reconfigurable photonic signal processor with programmable all-optical complex coefficients. IEEE Trans. Microw. Theory Technol. 58, 3088 (2010)

156. R. Moreira, J. Garcia, W. Li, J. Bauters, J. Barton, M. Heck, J. Bowers, D. Blumenthal, Integrated ultra-low-loss 4-bit tunable delay for broadband phased array antenna applications. IEEE Photonics Technol. Lett. 25, 1165 (2013)

157. Y. Liu, J. Yang, J. Yao, Continuous true-time-delay beamforming for phased array antenna using a tunable chirped fiber grating delay line. IEEE Photonics Technol. Lett. 14, 1172 (2002)

158. J. Cardenas, M. Foster, N. Sherwood-Droz, C. Poitras, H. Lira, B. Zhang, A. Gaeta, J. Khurgin, P. Morton, M. Lipson, Wideband continuously tunable optical delay line using silicon microring resonators. Opt. Express 18, 26525 (2010)

159. T. Tatoli, D. Conteduca, F. D’Olio, C. Ciminelli, M. Armenise, Graphene-based fine-tunable optical delay line for optical beamforming in phased-array antennas. Appl. Opt. 55, 4342 (2016)

160. J. Cruz, B. Ortega, M. Andres, B. Gimeno, D. Pastor, J. Capmany, L. Dong, Chirped fibre Bragg gratings for phased-array antennas. Electron. Lett. 33, 545 (1997)

161. M. Chen, H. Subaraman, R. Chen, Photonic crystal fiber beamformer for multiple X-band phased-array antenna transmissions. IEEE Photonics Technol. Lett. 20, 375 (2008)

162. X. Ye, F. Zhang, S. Pan, Compact optical true time delay beamformer for a 2D phased array antenna using tunable dispersive elements. Opt. Lett. 41, 3956 (2016)

163. G. Valley, Photonic analog-to-digital converters. Opt. Express 15, 1955 (2007)

164. P. Juodawlkis, J. Twichell, G. Betts, J. Hargreaves, R. Younger, J. Wasserman, F. O’Donnell, K. Ray, R. Williamson, Optically sampled analog-to-digital converters. IEEE Trans. Microw. Theory Tech. 49, 1840 (2001)

165. J. Capmany, B. Ortega, D. Pastor, A tutorial on microwave photonic filters. IEEE J. Lightw. Technol. 24, 201 (2006)

166. L. Zhuang, C. Roeloffzen, A. Meijerink, M. Burla, D. Marpaung, A. Leinse, M. Hoekman, R. Heideman, W. Etten, Novel ring resonator-based integrated photonic beamformer for broadband phased array receive antennas—part II: experimental prototype. IEEE J. Lightw. Technol. 28, 19 (2010)

167. H. Kumawat, M. Chakraborty, A. Bazil R, S. Davale, DIAT-μSAT Small Aerial Targets’ Micro-Doppler Signatures and their Classification Using CNN. IEEE Geosci. Remote Sens. Lett. 19, 1 (2022)

168. F. Scotti, F. Laghezza, P. Ghelfi, A. Bogoni, Multi-band software-defined coherent radar based on a single photonic transceiver. IEEE Trans. Microw. Theory Tech. 63, 546 (2015)

169. F. Laghezza, F. Scotti, P. Ghelfi, A. Bogoni, S. Pinna, Jitter-limited photonic analog-to-digital converter with 7 effective bits for wideband radar applications, in IEEE Radar Conf. (RadarCon13) (2013), p. 1

170. Y. Han, O. Boyraz, B. Jalali, Ultrawideband photonic time-stretch A/D converter employing phase diversity. IEEE Trans. Microw. Theory Technol. 53, 1404 (2005)

171. J. Chou, J. Conway, G. Seller, G. Valley, B. Jalali, Photonic bandwidth compression front end for digital oscilloscopes. J. Lightw. Technol. 27, 5073 (2009)

172. F. Scotti, D. Onori, F. Laghezza, Fully coherent S-and X-band photonics-aided radar system demonstration. IEEE Microw. Wireless Compon. Lett. 25, 757 (2015)

173. P. Ghelfi, F. Laghezza, F. Scotti, D. Onori, Photonics for radars operating on multiple coherent bands. J. Lightw. Technol. 34, 500 (2016)

174. W. Zou, H. Zhang, X. Long, S. Zhang, Y. Cui, J. Chen, All-optical central-frequency-programmable and bandwidth-tailorable radar. Sci. Rep. 6, 1 (2016)

175. V.S. Chernyak, Fundamentals of Multisite Radar Systems: Multistatic Radars and Multistatic Radar Systems, 1st edn. (CRC Press, 1998)

176. X. Zou, W. Li, B. Lu, W. Pan, L. Yan, L. Shao, Photonics approach to wide-frequency-range high-resolution microwave/millimeter-wave Doppler frequency shift estimation. IEEE Trans. Microw. Theory Technol. 63, 1421 (2015)

177. G.R. Song, Xixi, Z. Yonggang, P. Shilong, Experimental demonstration of a GPS-over-fiber multi-antenna receiver system. J. Data Acquis. Process. 06, 957 (2014)

178. S. Pan, J. Yao, Photonics-based broadband microwave measurement. J. Lightw. Technol. 35, 3498 (2017)

179. Xihua Zou1, Bing Lu1, Wei Pan1, Liandan Yan1, Andreas Stühr, Jianping Yao, “Photonics for microwave measurements”, Laser Photonics Rev. 10, 711 (2016)

180. V.C. Chen, F. Li, S.-S. Ho, H. Wechsler, Micro-Doppler effect in radar: phenomenon, model, and simulation study. IEEE Trans. Aerosp. Electron. Syst. 42, 2 (2006)

181. F. Alimenti, F. Placentino, A. Battistini, G. Tasselli, W. Bernardini, P. Mezzanotte, D. Radicio, V. Palazzari, S. Leone, A. Springer
Scaponi, N. Porzi, M. Gomez, L. Roselli, A low-cost 24GHz Doppler radar sensor for traffic monitoring implemented in standard discrete-component technology, in *IEEE European Microwave Conference* (2007), p. 1441

182. A. Tessmann, S. Kudszus, T. Feltgen, M. Riessle, C. Sklarczyk, W. Haydl, Compact single-chip WbandFMCWradar modules for commercial high-resolution sensor applications. IEEE Trans. Microw. Theory Technol. **50**, 2995 (2002)

183. B. Mencia-Oliva, J. Grajal, O.A. Yeste-Ojeda, G. Rubio-Cidre, A. Badolato, Low-cost CW-LFM radar sensor at 100 GHz. IEEE Trans. Microw. Theory Technol. **61**, 986 (2013)

184. X. Zou, W. Li, B. Lu, W. Pan, L. Yan, L. Shao, Photonic approach to wide-frequency-range high-resolution microwave/millimeter-wave Doppler frequency shift estimation. IEEE Trans. Microw. Theory Technol. **63**, 1421 (2015)

185. B. Lu, W. Pan, X. Zou, X. Yan, L. Yan, B. Luo, Wideband Doppler frequency-shift measurement and direction ambiguity resolution using optical frequency shift and optical heterodyning. Opt. Lett. **40**, 2321 (2015)

186. Defense and National Security/Optics and Photonics: Essential Technologies for Our Nation (The National Academies Press), https://www.nap.edu/read/13491/chapter/6. Accessed 4 Jun 2012

187. Missile Defense Agency, U.S. Department of Defense, *Airborne Laser Test Bed Successful in Lethal Intercept Experiment* (MDA News Release, 2010), http://www.mda.mil/news/10news0002.xhtml. Accessed 2 Aug 2012

188. B. Lu, W. Pan, X. Zou, Y. Pan, X. Liu, L. Yan, B. Luo, Wideband microwave Doppler frequency shift measurement and direction discrimination using photonic I/Q detection. J. Lightw. Technol. **34**, 4639 (2016)

189. L. Maccone, C. Ren, Quantum radar. Phys. Rev. Lett. **124**, 200503 (2020)

190. M. Lanzagorta, Quantum radar cross sections. Quantum Opt. **7727**, 77270K (2010)

191. D. Luong, S. Rajan, B. Bhashyam, Entanglement based quantum Radar:from a myth to reality. IEEE A&E Systems Magazine **35**, 22 (2020)

192. F. Daum, Quantum radar cost and practical issues. IEEE A&E Syst. Mag. **35**, 11 (2020)

193. A. Salmanogli, D. Gokcen, H. Selcuk, Entanglement sustainability in quantum radar. IEEE J. Sel. Top. Quantum Electron **26**, 1 (2020)

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