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Review Article

Recent Advances in Photonics Radar: A Review

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Abstract *- Modern radar systems developed mainly for military applications during the 1940s use radio waves to detect a target, its distance, radial velocity and size. Today radar has been applied successfully to numerous applications for civilian purposes as well. Smaller target detection in real-time with high resolution by radar needs high frequency and large bandwidth. Today's electronics systems are limited by the smaller bandwidth, Analog-to-Digital Converter (ADC) noise, low speed, low resolution and reduced sampling precision. Present-day targets such as Uncrewed Aerial Vehicles (UAVs) flying at low altitudes with low speeds and smaller sizes need radar signals to have ultra-stable phase and ability to operate at a wide range of frequencies. These requirements need electronics and photonics-based radar integration to detect small UAVs with high resolution and speed. Even though demonstrable photonics radar was only presented in the year 2014, subsequently, numerous research studies have been done on this promising field. Photonics technology for radar is a well-discussed topic in reviews, and photonics radar as a system is minimally reviewed. Radars for small targets have been developed and offered in different types and bands of operations. It is, therefore, the need of the hour to dwell in the radars developed by photonics technologies for small targets. This paper discusses the photonic radar technology and surveys all the available literature leading to inferences helping in future directions in this field of research. The main contribution of the review is a summary of photonics radar, which is tabulated showing the bands used, type of target, range and radar type. The work directs the use of photonics-based radar for their large time-bandwidth product and operation at wideband, even at gigahertz, where no change in performance related to frequency is seen. It is also concluded that photonics radar operating in the X band is the best choice for targets such as UAVs, leading to higher Radio Cross Section (RCS), thereby increasing range.*

Keywords *- LSS targets, Microwave photonics technology, Photonics radar, Uncrewed aerial vehicle, Target detection.*

1. Introduction

Radar, abbreviated as Radio Detection and Ranging, is a word in the modern dictionary. A radar is a system that can detect an object, which is usually called a target, and its range, size, and mobility by transmitting and receiving electromagnetic waves reflected from the target [1]. The bandwidth of the signal used in radar dictates the range resolution. A higher bandwidth is needed for higher range resolution. Multi-function radar with anti-jamming and anti-intercept capability and radars used for detecting and classifying low altitude, small Radar Cross Section (RCS) targets, and slow speed (LSS) targets require very high bandwidth. In addition, LSS target detection needs a stable phase magnitude relationship with fewer phase noise signals. These requirements can be met by photonics (electro-optic approach) based radars [2]. Devices with flat magnitude achieve in-band noise and interference removal by coherent cancellation, and phase responses can only be obtained for narrow-band signals in electronic-based systems. It is found that 7° of phase variation is seen for signals of 30 GHz. Coherent cancellation is effectively done in photonics systems with flat magnitude and phase response. J. Wu, K. Wang and Y. Gu [3], in their research, point out four important criteria for futuristic radar applications such as wider bandwidth, operation at high speeds, provisions for parallelism and efficient integration. The research shows that photonics-based radar can satisfy these four characteristics. The research tabulates the bottleneck problems associated with present-day electronics, such as the instantaneous bandwidth required is around 5 GHz ~ 10 GHz and future demand above 20 GHz, whereas the electronic domain can provide only about 2 GHz. The multiply and accumulate operation for 20 GHz may need sixteen thousand Multiply and Accumulate (MAC) operations when 32-bit quantization is performed. To realize such a massive computational complexity, a greater number of Field Programmable Gate Arrays (FPGAs) are required in the electronics domain.

Delay lines needed for broadband signals with low loss can be achieved in the optical domain with optical fibers.

Radio Frequency (RF) systems using DSP techniques cannot satisfy the demands when wide bandwidth signals are used. For example, in analog-to-digital Converters (ADCs) root mean square timing jitter is nonnegligible at sampling in femtosecond. The fastest available ADC from Texas Instruments is ADC12DJ5200RF. This ADC can work with signals of 8-GHz bandwidth and can produce 10.4-gigasamples-per-second (GSPS). However, the high-resolution radars require bandwidth greater than 18 GHz [4]. In addition, modulation, down and up conversion, filtering, phase detection, and other operations done in the electronic domain can be done bettersing photonics [2].

Present-day low-flying UAV targets necessitate revisiting the application of general electronics-based radars for such applications. Integrating photonics and electronics for radar is gaining popularity and must be considered. Therefore, the objective of this paper is to discuss the photonics radar and its various implementations, highlighting the type, size and mobility of targets used, the range used for experimentation, the resolution obtained, the photonic technologies used and possible applications. The second objective of this work is to infer from this survey to guide the researchers in selecting a suitable technology for small UAVs as targets. Section 1 provides the importance and advantages of photonics in modern radar applications; Section 2 points out the gaps in the review paper published on this topic; Section 3 explains the general architecture of photonics-based radar construction and works as a block diagram highlighting the suitable technologies for each block. Section 4 discusses about various works done in the field of photonic radar from the year 2014. Section 5 summarizes the work on target detection and requirements for photonics-based radar for complex targets such as drones. Section 6 concludes the work, followed by references.

2. Gaps in Existing Reviews

The review of photonics radar will be very useful for people who wish to work in this field. It has been found that there are very few research papers that give a review on this topic. In this section, the available review articles are discussed. In a review by Borowski et al. [5], the authors were able to discuss limited areas pertaining to photonics radar, such as the need for photonics radar and the limitations of microwave electronics. The work has contributed to explaining the photonic radar subsystem. The work also highlighted the principles and workings of the first photonic radar,hich was implemented and field-tested [6]. It has to be noted that this work is introductory in nature, and its content is limited. In an invited review paper [2], features of microwave photonics were discussed in depth. Bandwidth, high-performance signal transmission, multidimensional multiplexing, broadband analog signal processing, good phase response and highly coherent pulse source were discussed in detail. In addition, photonics technologies such as photonics-based signal generation, mixing, filtering, beamforming, and ADC were detailed in depth. The review also has a photonics-based radar architecture. The following year, a review paper by Panda et al. [7] discussemicrowave photonics radar's advances and future directions. This work highlighted the developments in the devices used in microwave photonics radar. The work also discussed similar topics as seen in [8] and [2]. The difference in this work lies in future improvements and the direction in which research and development must be done. The areas of improvement needed in current photonics radar are identified as ADC, high power handling photo diode and optical filters for wideband applications. The article also highlights the possibilities of extending phased array antennas for multi-functions. The work points out the bulky nature of photonics radar and recommends size reduction in photonics radar by using integrated technologies. It is seen that this work has most of the information that has been seen in earlier reviews except for the future directions.

In [9], the authors review photonics radars and, again, mostly on the topics discussed in the earlier reviews. The article uses a block diagrammatic approach to highlight the applications of radar and different types of ADC used in photonics radar. The article does not clearly show any advancements in the photonics radar, as stated in its title. In [10], a detailed review of microwave photonics techniques is discussed, along with the necessary equations. The article fully focuses on microwave photonics components, their behavior and cost. The cost of such devices, which can be reduced by progress in integrated microwave photonics, is clearly shown. The article also concludes by giving recommendations on using Si and InP for devices that couple fiber to chips and all other devices to use Si. The article is good for starters in the area of microwave photonics technologies. It was found that this article does not focus on any particular application, and the discussion on photonics radar is minimal. A survey on photonics technologies for radar applications [11] is an article close to the work done in this research. This work has elaborately discussed the history of radar till the advent of a full photonics radar PhoDIR system. General Microwave-Photonic radar system architecture is extended to multi-function and distributed radar. This work is an extension of the work done by one of the authors, which can be seen in [12], which was very preliminary but was one of the few available review articles during the time of its publication. Again, this work focuses mainly on photonics technology, such as signal transportation, detection, filtering, multiplexing, beamforming and analog-to-digital conversion, which are seen in earlier works. Contemporary applications of photonics radar technology are one area in which this work differs from the above works. This work has given a wide spectrum of applications of microwave photonics radar in landslide monitoring, global positioning, target detection, light detection and ranging, thermal detection, etc. It is seen that the discussion was only introductory and had no technical explanations. The review paper tried to cover a wider area related to photonics radar but failed to convince a reader to use this work as a starting point for a reader to work on photonics radar.

It can be very well seen from the above discussion that there is a gap in the literature survey on photonics radar for target detection. It is, therefore, concluded that.

a. No work has discussed in depth the available types of radars which can be used for target detection.
b. Photonic radar for small targets such as UAVs is compared.
c. The advantages of the X band for targets with moving parts are presented in the previous reviews.

Advances in photonics radars, which can show better results in determining the parameters such as range, target dimension, target speed and capability of dealing with small-sized targets, are not available or discussed. This work reviews photonics radars used for target detection in depth.

3. Features of Photonic Radar Systems

3.1. General Description of a Photonic Radar

The photonic radar system has electronic and photonic devices/components working together to remove shortcomings using the electronic domain alone. A simple block diagrammatic approach showing the construction and working of a photonic radar system is given in Figure 1. It consists of three subsystems: photonics-based RF signal generation, photonics-based down conversion and a signal processing subsystem with display.

In the transmitter, a stable oscillator at the baseband (BB) of the Intermediate Frequency (IF) band can be easily realized in the electronics domain. Thereafter, a mixer and a bandpass filter are upconverted the signal in multiple stages. In the electronic domain, amplitude and phase noise are generated at each stage, and they are significant. The stability of the local oscillator decreases with an increase in frequency, and the coherence between oscillators is also of concern as they use different frequencies at different stages. Spurious levels are also an added concern in the above scheme. It is found that photonics-based signal generation can lower the above issues. In the photonics-based system, the RF signal generation is done in the photonics domain by an Optical Modulator (OM) amplified by an Optical Amplifier (OA) and converted to the electrical domain by a Photo Diode (PD). In the receiver, the Optical Phase Modulator (OPM) is based on Pockels cells, and controlling the phase of the incoming optical signal allows advanced signal processing. The OPM receives the optical generated signal from an Optical Coupler (OC) and the electrical signal from the Low Noise Amplifier (LNA). Beat frequency, for example, can be extracted after this stage by proper filtering and processing.

3.2. Microwave Photonic Link

The Microwave Photonic Link (MVP) link has an optical source such as a pump laser with wavelength 1550 nm @ 8 dB connected to an Electro-Optic Modulator (EOM) such as a Machzendar modulator (MZM) and amplified by an optical amplifier followed by a photodiode. The link/cable/channel that connects various electronic and photonic devices in the photonic radar is a fibre optical cable. The optical signal at the wavelength range of 1510 nm to 1600 nm has the lowest loss and is flat across the range. Fibre cable has various advantages over its electronic counterpart, such as coaxial cable.

The up-and-down conversion that occurs in such links will degrade the fidelity of the RF signals. The degrading can be quantified and studied through metrics such as RF gain, Spur Free Dynamic Range (SFDR), Compression Dynamic Range (CDR) and RF noise figure [13]. The RF gain and RF noise figure are given by Equations 1 and 2.

$$G_{rf}(dB) = P_{rf,out}(dB) - P_{rf,in}(dB) \tag{1}$$

$$NF_{rf}(dB) = N_{out}(dBm/Hz) - G_{rf}(dB) + 174 \tag{2}$$

SFDR gives the measure of the purity of the signal. The purity in the link may be disturbed by nonlinear mixing, which

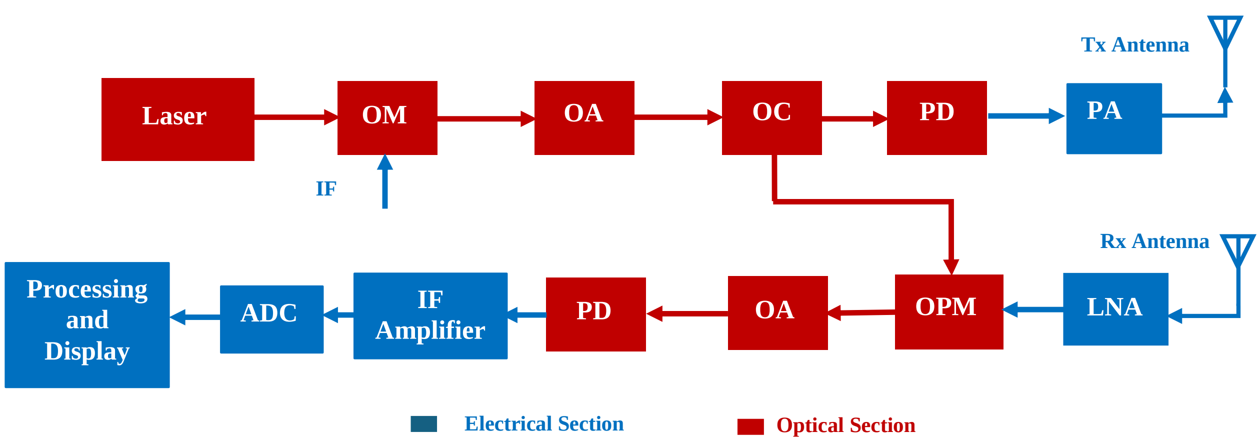

Fig. 1 General block diagram of a photonics radar

produces harmonic and/or spurious intermodulation signals. Spurious signals occur at second and third harmonic frequencies, and even order harmonics can be easily suppressed, leaving behind the odd order (in this case, 3rd order) spurs as disturbance. The SFDR can be calculated by plotting the RF input power versus the RF output power graph. A model is shown in Figure 2. The SFDR is for the third harmonic and is given by the Equation 3.

$$SFDR_3(dB.Hz^{\frac{2}{3}}) = \frac{2}{3}[OIP_3(dBm) - N_{out}(dBm)] \quad (3)$$

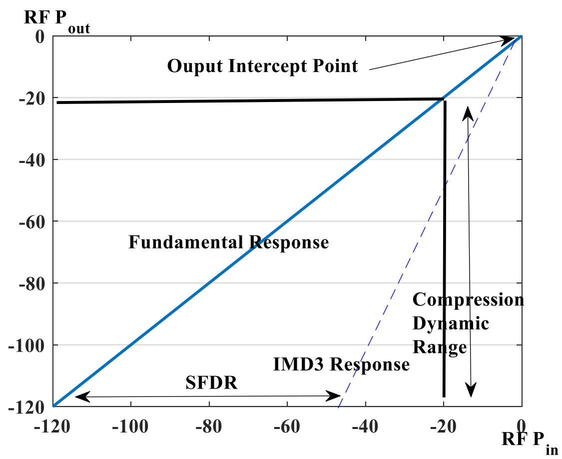

Fig. 2 The metrics of a microwave photonics link [13]

The CDR is a range taken from the fundamental response curve. The starting point is 1 dB below the ideal response, and the endpoint is the noise floor. In the diagram, the noise floor is -120 dB and below. It is given by Equation 4.

$$CDR(dB.Hz) = P_1 dB(dBm) + 1 - N_{out}(dBm) \quad (4)$$

A photonics link generally has a significantly higher spurious-free dynamic range (SFDR) than a microwave link due to its inherent lower noise levels and ability to effectively suppress distortion, making it superior for applications requiring high signal fidelity and wide dynamic range.

3.3. Light Sources

Light amplification by stimulated radiation emission (Laser) is usually a semiconductor device capable of generating coherent light where all waves are at the same frequency and phase. The working of the laser diode starts with the absorption phase, where electrons absorb energy and get itself transferred to a higher energy level for a period of time called recombination time. Then, the next stage starts, which is called the spontaneous emission stage, after the recombination time has elapsed. In this stage, electrons fall from a higher energy level to a lower energy level, and the difference is converted into photons or electromagnetic radiation[14]. There can be other methods called stimulated emission where photons are made to strike electronics at a higher energy level where these photons are produced from an external light source. Amplification takes place in this configuration. The output can also be fed back into a laser resonator to produce oscillation. The laser usually has a diode structure with type PIN (electrically a PIN diode), where I stands for intrinsic or non-diode based, such as quantum cascade lasers and optically pumped semiconductor lasers. The wavelength of a laser diode is dependent on the band gap of the laser-active semiconductor material. The composition of ternary and quaternary semiconductor compounds can be changed to obtain various wavelengths. AlGaInP / GaAs produces 635, 650, and 670 nm wavelength lasers, which are used in DVD players and AlGaInP / GaAs, producing light waves at wavelength 1.2 to 2 µm is used in optical communications[14].

Various types of lasers are available and classified in terms of

- Region of emission as edge emitters and surface emitters.
- Output power
- Wavelength
- Bandwidth
- Distributed Bragg reflector lasers (DBR lasers)
- Distributed feedback lasers (DFB lasers)

3.4. Generation of Microwave Carrier by Photonics

The phase noise of the signal produced increases by 6 dB for every doubling of the frequency. The RF signal generation by photonics has advantages in terms of low phase noise, low loss, high bandwidth and low electromagnetic interference (EMI). IMPATT diode and Gunn diode can produce carriers at GHz but with phase noise more than photonic-based generation. It helps in radar systems such as multiband multifunctional radars where frequency-specific electronic devices will not provide any of the above advantages [15].

Photonic generation of RF signals can be classified into two types 1). Optical Heterodyne, and 2). Pulsed. In the Optical Heterodyne type, there can be further classification as a). dual laser b). external modulation, and c). optical frequency comb combined with a filter. Further, in pulsed type, passive mode locking and active mode locking are the subtypes [16].

In the dual laser generation type, two single-frequency semiconductor lasers are mixed in a photodiode or photoconductor. The output is the difference in the optical wavelengths denoted as $f_{beat} = c|\lambda_1 - \lambda_2|/(\lambda_1\lambda_2)$. Such a device is a straightforward, cost-effective solution with a large frequency drift. Various solutions, including phase locking schemes such as optical injection locking optical phase-locked loop, can increase stability [16]. In the external modulation method, a combination of continuous lasers followed by a

MZM is used. Here, the stability is better than the dual laser type, and the phase depends only on RF source phase noise. This method produces a double side band suppressed carrier whose wavelengths are twice that of the RF synthesizer. The modulator bias input and structure are made in such a way as to do the above job.

Additional complex structures can also obtain higher multiplication factors. To circumvent this, an optical frequency comb generator is used. This method generates more wavelengths with a fixed frequency spacing between them. This method is well-suited for applications where reconfigurable generators are needed. The phase noise, in this case, is directly proportional to $M^{2,}$ where M is the multiplication factor. Therefore, this method is inferior to the external modulation method.

Even though lasers operate in continuous mode (by the addition of a laser cavity to circulate with a gain medium) in single frequency or multiple frequencies, they can also be used to create pulses. The pulsed operation is done by mode locking where inside the laser resonator, an active linear device such as an optical modulator or a nonlinear passive element such as a saturable absorber is added to produce a train of pulses.

There is another method to generate RF carriers by photonics techniques with ultra-low phase noise and the capability for in-chip integration called an optoelectronic oscillator (OEO), as shown in Figure 3. This type of RF signal generator was made attractive by Yao and Maleki [17]. Electrical and optical signals are combined by a loop, as shown in Figure 3, which produces signals in micro and millimeter waves. The frequency is determined by the fiber loop, bias setting and the electrical filter.

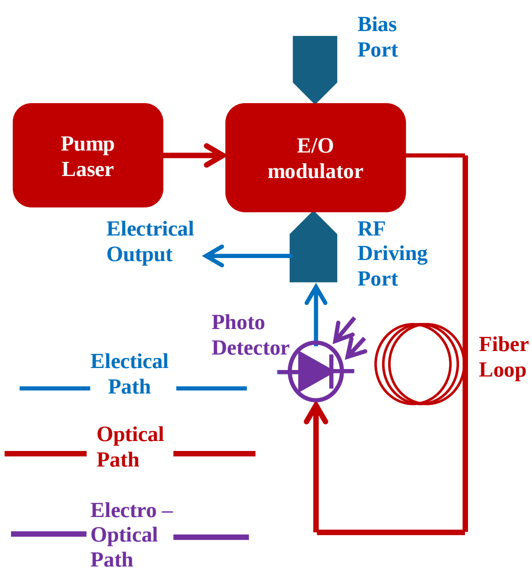

Fig. 3 Basic block diagram of an Optoelectronic Microwave Oscillator (OEO)

The OEO has a laser, E/O modulator, long optical fibre and photodetector. Light from the laser is sent through a long fibre cable (which introduces delay) to a photodetector. The output of the photodetector is an RF signal, which is fed back to the E/O modulator [17].

3.5. Optical Modulators

Electro-optical modulators (EoM) are one of the main components of a photonics radar. A simple arrangement to produce modulation is shown in Figure 4. In EoM, the energy, phase and polarization of the optical signal are controlled by an applied voltage. This control is done by the Pockels effect. Pockels effect is done by applying an electric field to produce changes in the refractive index of an optical material. Pockels effect is seen in crystals made of lithium niobate (LiNbO3), silicon carbide and some organic compounds (special poled polymers) [18]. Small form factor, CMOS compatible platform, gigahertz bandwidth, lower drive voltages V and higher frequency operation, power handling, index contrast, Frequency Response, etc., are the parameters associated with EoMs. In this case, the electrical signal can change the light beam's phase, amplitude, or polarization. The relation between change induced by the electrical field E is given by

$$\Delta(\eta)E = r_{EO}E + P_{EO}E^2 \tag{5}$$

r_{EO} and P_{EO} are linear and quadratic electrooptic coefficients; the former is called the Pockels effect, and the latter is known as the Kerr Effect.

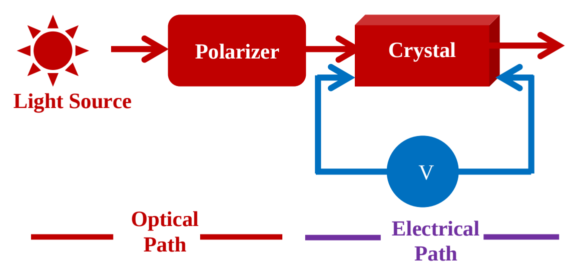

Fig. 4 A simple arrangement for modulation in the photonics domain

The variation of refractive index by linear electro-optical coefficient Pockels effect is

$$\eta' = \eta_0 \pm \frac{1}{2}{\eta_0}^3 r_{EO}\left(\frac{V}{L}\right) \tag{6}$$

Where η' is the change in refractive index, η_0 is the initial refractive index, V is the applied voltage, and L is the length of the crystal. In this system, the change in the phase of the light wave passing through the crystal is given by

$$\Phi = \frac{2\pi}{\lambda}{\eta_o}^3 r_{EO}V \tag{7}$$

FMCW waveform generation from an EoM is seen in Figure 5 [19]. This is basically a single sideband suppressed carrier modulator made by two MZM modulators and a quadrature electric coupler. The arrangement shown in Figure 5 splits the optical signal (1 x 2) into two branches where the bottom branch undergoes 90^0 phase shift, and the upper branch is unaltered. The lower sidebands have a 180° phase difference, and the upper sidebands from the two MZM maintain the same phase. When these two signals are combined (2 x 1), the lower sidebands cancel each other, and the upper sideband, which is the sum of ω_c and ω_m alone, is generated. It is argued that if ω_m is swept across a frequency range, the carrier will also be swept, thus generating a FMCW signal.

There are other photonics-based methods to generate FMCW waveforms, such as

- Space-to-time mapping (STM)
- Frequency-to-time mapping (FTM)
- Heterodyning of a linearly chirped optical pulse with a continuous wave (CW) light

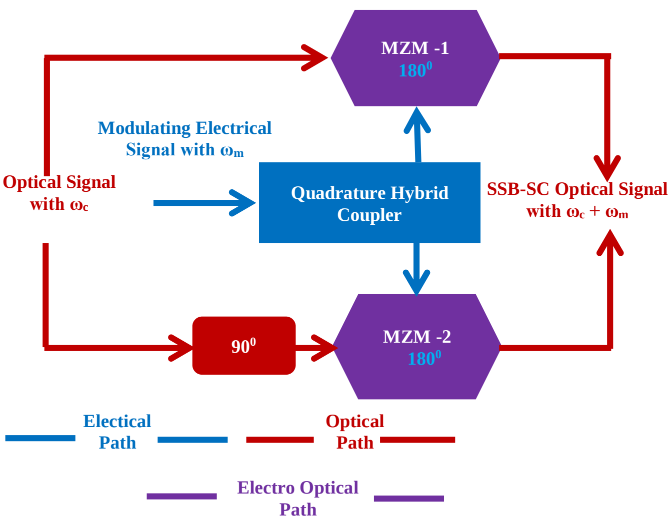

Fig. 5 FMCW waveform generation from an EoM

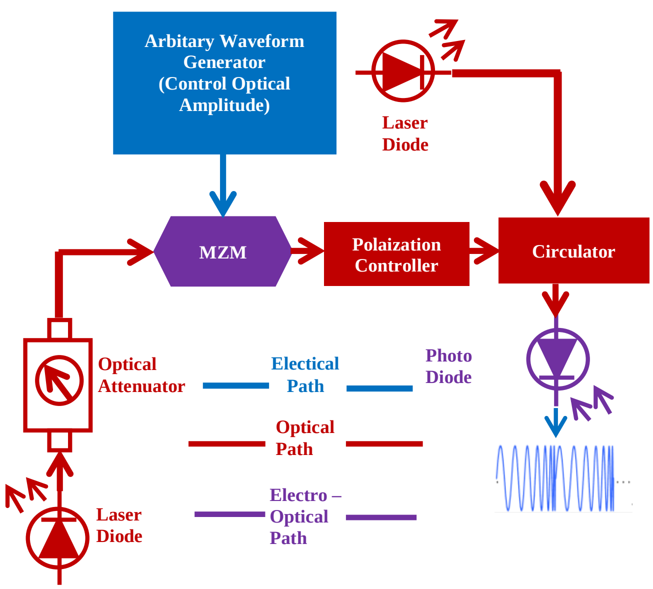

Fig. 6 FMCW waveform generation by optical injection

One method that can generate an FMCW waveform with a large Time-Bandwidth Product (TBWP), which is impossible in the electronic domain, is by an optically injected semiconductor laser. This method is shown in Figure 6.

The method shown in Figure 6 is superior to other methods in terms of simplicity and compactness and ability to generate FMCW waveforms with a bandwidth of 12 GHz and temporal duration of 10 µs (Zhou et al. 2016).

The system has two lasers in which a continuous optical wave with frequency f_m from the master is injected into a slave with a free-running frequency f_s. A polarization controller is used to align the polarization of the master laser with that of the slave laser for maximum injection. Now, the master laser frequency is detuned with the help of the slave laser to a frequency $f_1 = f_m - fs$ where a continuous wave light with frequency is generated in master laser fm. A variable optical attenuator can be added to control the power of the injection. Now, the slave laser is operated in the P_1 oscillation state, and it gives two signals with regenerated carrier frequency f_m and f_s'. The output of the slave laser, when sent to a photodiode, will generate a signal with frequency $f_0 = f_m - f_s'$. When the detuning frequency and/or the injection strength are changed, the output frequency from the photodiode is changed linearly.

3.6. Photodetectors and RF Conversion

Photodetectors are sensors that convert light energy into electrical energy (O/E converter). There are many types of photodetectors, and they are classified based on the mechanism of operation or their device structure. Semiconductor (InGaAs and Ge are commonly used mature technology) based photodetectors, particularly diode structures, have characteristics suitable for radar applications. The characteristics needed are high-frequency operation, smaller sizes, fast detection speed, and high detection efficiency. In diode-based photodetectors, PIN PD and the Avalanche Photodetector (APD) are the two main types. APD has higher sensitivity but has disadvantages, such as the need for complex bias circuits and epitaxial wafer structures and the role of both shot noise and thermal noise [21]. PIN PD has improvements such as Velocity-Matched Distributed Photodetector (VMDP), Traveling-Wave Photodetector (TWPD), Uni-Traveling Carrier (UTC) PD, InGaAs/InGaAsP/InP modified uni-traveling carrier (MUTC), resonant-cavity-enhanced photodiodes, Schottky photodiodes, metal-semiconductor-metal photodetectors 21, 22]. The requirements are the ability to handle high power, possess high linearity, handling capability, large SFDR, high responsivity, low dark current, maintain high speed and the ability for system integration [22].

PIN diode has three regions: P region (heavily doped), N region (heavily doped) and hardly doped Intrinsic region (wide when compared to the depletion layer of PN junction diode). The photons, when incident on the intrinsic region, create electron-hole pairs. The electric field created by the PN junction separates these charges, and this results in the movement of electrons towards the N-type region and the movement of holes towards the P-type region. A current is produced due to this separation, which is detected. PIN PD can be modified with a thin P-type absorber where electrons are produced and accelerated towards the carrier. The electrons travel at ballistically high velocity in the collector; the photo response performance is better than the PIN diode and is called a Uni-Traveling-Carrier Photodiode (UTC-PD). In modified UTC, there is a hybrid absorber section. The introduction of this section leads to faster response and higher O/E conversion efficiency than UTC.

3.7. Optical A/D Converters

Analog-to-digital converters play an important role in modern communication systems, which convert analog signals to digital signals for processing. The system accuracy number of bits, which is related to resolution and conversion speed, is the important factor to be considered while choosing an ADC. The resolution = 2^n where n is the number of bits for each sample where n-bit ADC gives 2^n –1 digital state. The resolution of a 3-bit ADC converter has $2^3 = 8$ number of states where each state is encoded with 3 bits. An 8-bit A/D has 256 states for an analog signal with a 20 V range and resolution of 78.1 mV. If a similar signal is digitized using a 20-bit ADC, there will be 1048576 states with a resolution of 19.1 µV. The conversion speed clock of an ADC with a frequency of 100 kHz will have a sample rate of 100 kSPS and a conversion time of 10µs. It implies that the above clock is suitable for signals less than 50 KHz. What if the analog input signal is 10 GHz. The clock should operate at 20 GHz and above with 10 GSPS. The sampling time interval is $1/10e^9$ or 0.01 ns.

The four different architectures to realize a photonic ADC are a) ADC, which is assisted by photonics; b) sampling done in the photonic domain and quantization done in the electronic domain; c) sampling done in the electronic domain and quantization done in photonic domain and d) sampling and quantization done in the photonic domain. [23]. The first three architectures require electronic-based sampling and/or quantization, which consume more power and take high complexity. The photonic sampling and quantization schemes have two types of architectures that are different in quantization methods: Optical Amplitude Quantization (OAQ) schemes and Phase-Shifted Optical Quantization (PSOQ) schemes. The OAQ scheme has difficulty in chip-level integration and comes with additional power. Upto 40 GS/s is demonstrated. In the PSOQ scheme, the quantization is carried out by the interference of the lights with different phases. Mach–Zehnder modulators (MZM) with identical half-wave voltages or multimode interference (MMI) couplers. State-of-the-art ADC can be easily integrated into a chip via a Thin Film Lithium Niobate (TFLN) platform and Pockels effect of lithium niobate, providing a linear modulation. A bandwidth of 80 GHz and V_π of 2.3 V modulator using MMI is demonstrated [24].

3.8. Photonic Time-Stretched Processing

The limitations of the ADC in the electronic domain are discussed in the previous section, especially when dealing with ultrabroad millimeter-wave radar signals. Photonic ADCs are newer technology where sampling and quantization can be done in the optical domain with ease. However, they are in the nascent stage, and one alternative photonics-based technology is photonic time-stretch processing, which compresses the bandwidth before sampling can be done [25, 26]. It is a photonic preprocessing technique where the bandwidth of the received echo is time-stretched by passing it through a dispersive medium. The incoming high bandwidth received radar echo is stretched in time in a single-channel or multi-channel arrangement based on time-limited or continuous input. The process is shown in Figure 7. The stretch factor of M is used in time stretching, and then the sampling rate (equivalent) of the digitizer f_s is increased by M times, enabling electronic ADCs to work easily. It has also been shown that there is no impact on shot noise, and thermal noise limits SNR, which is an additional benefit of alleviating the SNR reduction due to jitter in the sampling clock [26].

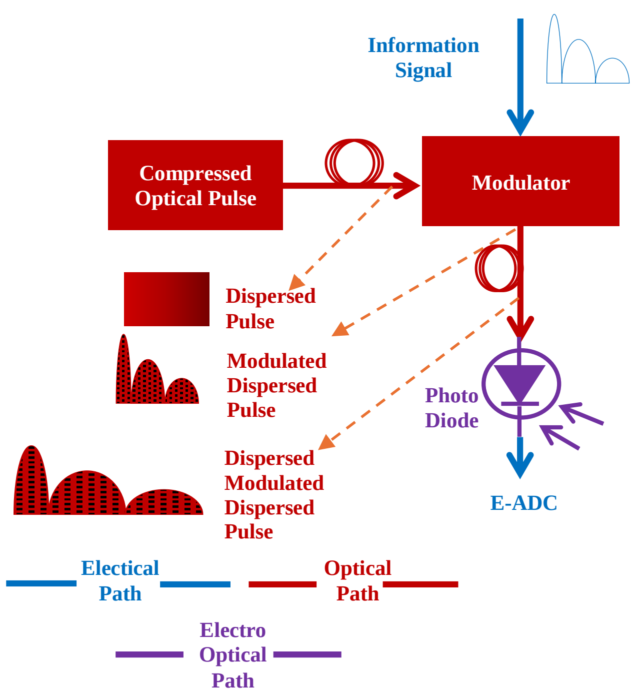

Fig. 1 Illustration of time- stretching process by photonics system

The process involved in the photonics-based time stretching shown in Figure 7 involves taking the received echo signal of the radar and modulating the wideband ultrasoft optical pulses. The modulated information is now sent through a dispersive element where the spectral components of the modulated signal spread in time. This brings the modulated signal spectrum to a lower level. Then, the photodetector is used to convert the signal to an electrical analog signal. An electronic digitizer completes the job. Time dispersion is done either by optical fibre with internal Raman amplification, chirped fibre Bragg grating, recirculating photonic filter, Spectral-to-angular-to-temporal mapping, chromomodal dispersion, etc. [27].

3.9. Optical Heterodyning

In Section 3.4, the photonic generation of RF signals by optical heterodyning was discussed in detail. The other usage of photonic heterodyning allows the conversion of very high-frequency signals to intermediate frequencies, followed by electronic ADC [28]. These downconverters can accommodate large bandwidth, are reconfigurable, and tunable with low loss and EMI. The methods demonstrated are based on a frequency-doubling optoelectronic oscillator, optomechanical oscillation, based on nonlinear effects, by a semiconductor optical amplifier (SOA) and using phase modulation and optical filtering [29].

The process of down conversion is done in three steps: the microwave signal is converted to an optical signal, mixing it with EOM with an electrical LO and converting it back to an electrical signal by a photodetector.

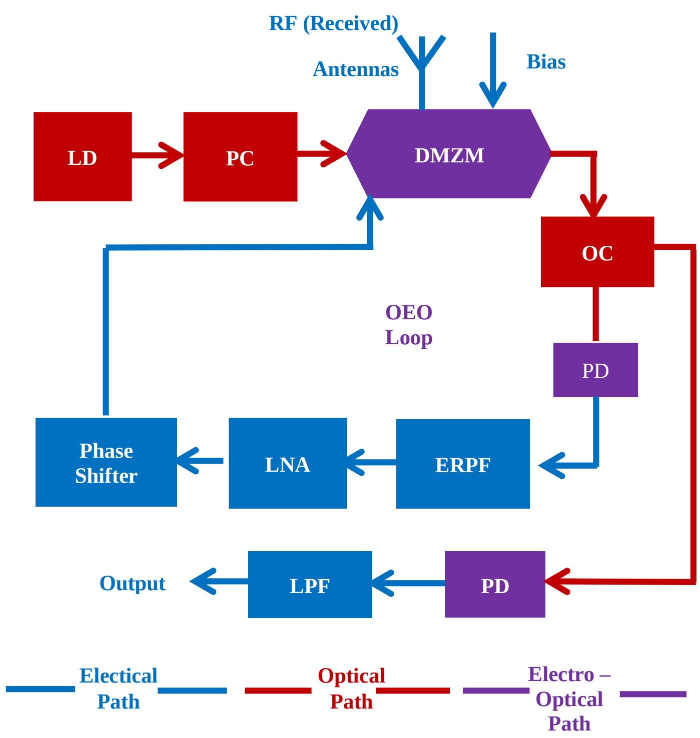

Fig. 2 Photonic-based RF down conversion using Opto-electro oscillator [30]

Figure 8 shows an RF downconverter where a single dual-drive MZM (DMZM) is fed by a CW laser diode (LD) and two RF inputs: one from the received signal and another from the optoelectrical oscillator (OEO) loop. The output of the DMZM is split via an optical coupler (OC), where one is sent to a lowpass filter (LPF) through a PD and the other to an electrical bandpass filter (EBPF) through a PD. This path, amplified by a low noise amplifier and fed to a phase shifter, is given in the RF port of DMZM. The central frequency of EBPF is kept close to the RF carrier frequency; thereby, the OEO loop will be injection-locked. In DMZM, the input reference input RF signal and extracted one are mixed in the optical domain [30]. The advantages of this method include high conversion efficiency, small size and low cost, avoidance of extra LO, and stable frequency down-conversion.

3.10. Optical Splitters, Circulators and Filters for MVP

An optical splitter, also called a fiber splitter or beam splitter, is a device that splits the incident light beam into two or more light beams. In photonic radars, a single-mode type of optical splitter is used and optimized for 1310nm and 1550nm operation. Insertion loss (smaller), return loss(larger), splitting ratio, and isolation are the parameters to be considered when choosing a splitter. The split streams can be equal or in some other ratio. The optical coupler is a device that can split optical signals and combine multiple optical signals. Fused Biconical Tapered (FBT) Splitters and Planar Lightwave Circuit (PLC) Splitters are the types of splitters. In the FBT type, single-mode fibers are bundled, fused, and tapered so that their diameter is of a single-mode fiber. When light enters, the power is distributed among the bundled fibers. In the PLC type, waveguides and thin film filters are arranged in a fashion so that when light enters, it is split. The advantage of PLCs lies in performance, unlike FBT, in terms of bandwidth and splitting ratio.

There are applications where bidirectional signal transmission takes place in optical and fiber, and there may be a need to separate them. An optical circulator is used and has the same characteristics as its electronic counterpart. It is a three or four-port device that, in three port configuration, emits the signal from the port when light is sent through port 1. In port three, the light, if any, is reflected back and sent out. High isolation and low insertion loss are the advantages of such devices.

The optical circulators work by Faraday effect. A Faraday material, when applied by a magnetic field, rotates the incoming light wave polarization plane. The angle of rotation is proportional to the Verdet constant of the Faraday material, as well as the magnetic field strength and length of the material.

Optical filters allow/reject optical signals with particular wavelengths. Shortpass filters, longpass filters, bandpass filters, and Notch Filters can be realized. Optical filters are placed after optical heterodyning. They can be realized by absorptive materials in glass plastic or Dichronic filters, which allow desired wavelength signals and reflect other wavelength signals. The second method is more complex and involves optical coatings of a particular thickness to do the job.

3.11. Photonic Balanced I/Q De-Chirping

Large bandwidth LFM signals are used in radars from ultra-high resolution and can be processed in real-time only with photonic-based de-chirping. Many demonstrations of real-time target detection imaging with ultra-high resolution capabilities are done using photonic de-chirping. Single-channel photonic frequency-mixing and balanced in-phase and quadrature (I/Q) de-chirp are two types available in the literature, where the latter results in a complex signal and the former with a real signal. Single-channel photonic frequency-mixing also suffers from interference and detection of false targets [31, 32].

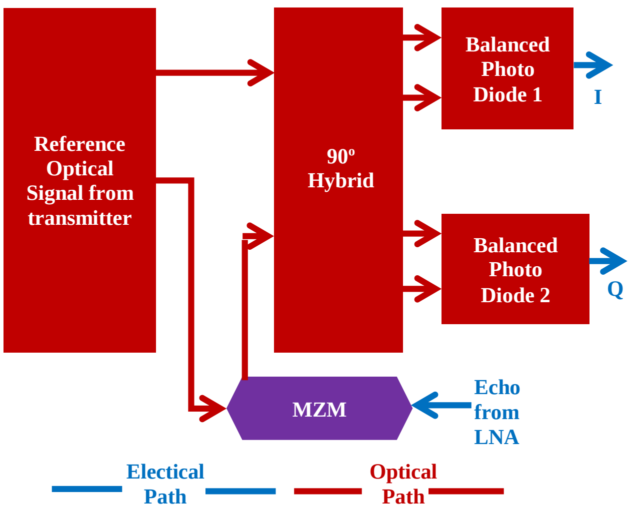

Fig. 9 Photonic-based I/Q dechirping

Photonics based I/Q de-chirping process is given in Figure 9. The received signal is broken into in-phase and quadrature-phase components. The main idea is to give a 90^0 optical delay to the received echo, and balanced photodiode detectors remove the common-mode terms.

3.12. Photonic Integrated Circuits

Reduction of the size of equipment and consumption of power are two objectives of any system, which can be done by using Integrated Circuits. Chip-based systems will be required furtheror drone-based or automobile-based radars [33]. With chip-based available for target detection upto a bandwidth of 1.5 GHz available, increasing bandwidth for higher resolution using photonics chip-based radar is expected [34]. In radar systems, using photonics devices along with electronic devices has shown improvement in all aspects of radar performance. Moreover, photons move along the circuit with less interference from other photons and at the speed of light, providing less heat. Indium Phosphide (InP), Gallium Arsenide (GaAs), Silicon Nitride (SiN) and Lithium Niobate (LiNbO3) are commonly used materials in PIC Implementation of photonics radar in integrated chips; therefore is, important aspect which has to be considered before taking the technology further. Most of the photonic radar implementations to present use discrete components, which are bulky systems and have low reliability. Integration circuit implementation of subsystems is done separately in many research studies, and some literature has fully implemented radar as a whole. In [33], works related to subsystems are shown. Those subsystems are integrated microwave photonic filter, microwave photonic true time delay line, optical beamformer, integrated optoelectronic oscillator [24], and programmable photonic signal processor chip.

In [33], a simple silicon photonic platform-based LFM radar was implemented on a CMOS-compatible platform with a size of 1.44 mm x 2.5 mm. The radar has a bandwidth covering 12 to 18 GHz distance measurement error of less than 2.75 mm and an ISAR resolution of 2.7 cm. It is simple in the sense that it has two MZM, a microring resonator and an optical coupler.

In [35], a photonic mmWave photonic LFM radar is implemented in an integrated circuit using 4-inch wafer-scale thin-film lithium niobate (TFLN) technology. This radar is capable of providing a multi-target ranging resolution of 1.5 cm, velocity resolution of 0.067 m/s, and ISAR images with a resolution of 1.5 x 1.06 cm. The advantages of de-chirping in the IC, the absence of filters, the tunability of the center frequency and bandwidth, and the operations at mmWave are good takeaways from this research. In addition, the Thin film lithium niobate (TFLN) platform has capabilities to overcome the limitations and disadvantages of Si Photonics-based technology in integrated circuit implementation.

Project SPACEBEAM (SPACE SAR system with integrated photonic BEAMforming) is another work that has shown the PIC in real-time implementation. Here, the main advantages were consuming low-power SAR systems with spatial resolution swath 5 times wider than the current spaceborne SAR systems. Four chips were designed and combined together. The first chip made up of InP has active components and is used for gain improvement in lasers. The second chip with InP was able to put an array of MZMs, which can be used for electrical and optical conversion and signal boosters. The third chip consists of passive elementsSi3N4 acting as a laser cavity. This system was able to do filtering, signal splitting combining and optical beamforming. The fourth chip, made up of InP, was able to accommodate an array of photodiodes for optical-electrical conversion [36].

Presently Cadence Design Systems, Inc. [37] has software packages called integrated Electronic/Photonic Design Automation environment (EPDA) PICs where most of the photonics devices used in radar such as waveguides, power splitters, waveguide reflectors, directional couplers, TE/TM polarizer, polarization beam, splitter, TE/TM converter, phase modulators, intensely modulators, frequency shifters and photodetectors had been implemented as chips.

4. State of the Art Photonics Radars

4.1. Classification of Photonics Radar

Photonics technology, which is well suited for radar, leads to all existing forms of radars, from pulsed radar to MIMO radar.

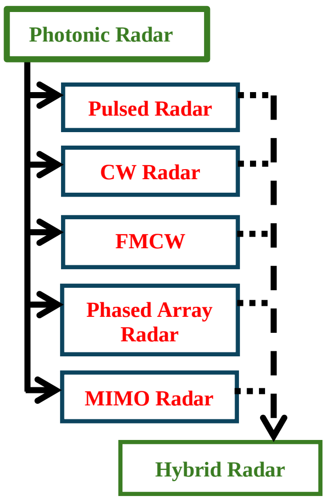

Fig. 10 Classification of microwave photonics radar

The literature also shows the hybridization of radar technologies to meet multiple requirements and use the advantage of one technology along with the other. The classification of photonics radar in the literature is summarized in Figure 10.

4.2. Pulsed Photonics Radar

Pulse Doppler radar sends a pulse and receives it when it is reflected by an object along with velocity (Doppler effect) and angle of the target (by using an array antenna). The time difference between the transmitted and received pulse(echo) helps find the range of the object by equation.

$$R = \frac{C\tau_R}{2} \tag{8}$$

Where C is the speed of light, and τ_R is the round trip delay of the pulse. Limited range and accuracy are the disadvantages of pulsed radar; however, they can use high-power pulses to detect small or low-reflecting targets. The half-duplex operation gives isolation between the transmitter and receiver, which helps to improve the dynamic range of the receiver.

The radar is also capable of detecting smaller objects under large clutters. This section discusses photonics-based pulsed radar, highlighting the benefits of using photonics to overcome the limitations and improve the performance of electronics-only radars.

Paolo Ghelfi1 et al. [7, 38] demonstrated the first fully functional photonics pulsed radar. In this work, RF signals at high frequencies (up to 40 GHz) were developed using the heterodyning method instead of an opto-electronic oscillator, which does not allow broad tuning. They have also used optical sampling, thereby avoiding aperture (less than 100 femto second in the optical domain) jitter produced by electronic ADCs. It has been shown that photonics-based radar is much more suitable for coherent radar.

The letter has compared the jitter produced by the state of art synthesizer and that of photonics-based and proved that the later is better. The radar system was tested on a field with an aeroplane as a target with 23 meters as distance resolution and 2 km/h as velocity resolution.

F. Scotti et al. [39] proposed dual-band pulsed radar based on photonics. This photonic radar uses a single radar instead of two when implemented by electronics-only radar. Two radars operating in the S (2-4 GHz) band and X (8-12 GHz) band are needed for applications where target discrimination and tracking are needed with high resolution. 9930 MHz and 2530 MHz are the two carrier frequencies used in the X and S bands, respectively. A moving target was used for demonstration where the X band gave higher Doppler estimation, and the S-band was immune against weather conditions.

In [38], the integration of photonics for radar is highlighted with the advantages of using coherent radio signals with different frequencies at the same time. This helps in obtaining multispectral imaging along with tunability, high bandwidth, and flexibility. This research is the continuation of the [39] where demonstratable pulsed photonics multiband radar was used.

The work highlights the limitation of direct digital synthesizers needed for multiple bands, which can only be used for RF signals with few gigahertz. The three important usages of photonics shown are (i) multiple signals with different frequencies simultaneously with high phase stability on the transmitter side, (ii) wide bandwidth ADC with a high sampling rate having low jitter and (iii) usage of optical fiber from the transceiver to antenna. The usage of optical fiber has further advantages, such as low noise, low loss, and EMI immunity.

The research also demonstrates phonics-based antenna beam steering, filtering in the optical domain and easy manufacturing techniques for photonics Integrated Chips (ICs). The radar was tested on targets such as boats for single-frequency operation and aeroplanes for multiple-band operation. It was found that the range resolution obtained with the data, which is merged from two bands, is approximately twice that of a single-frequency band.

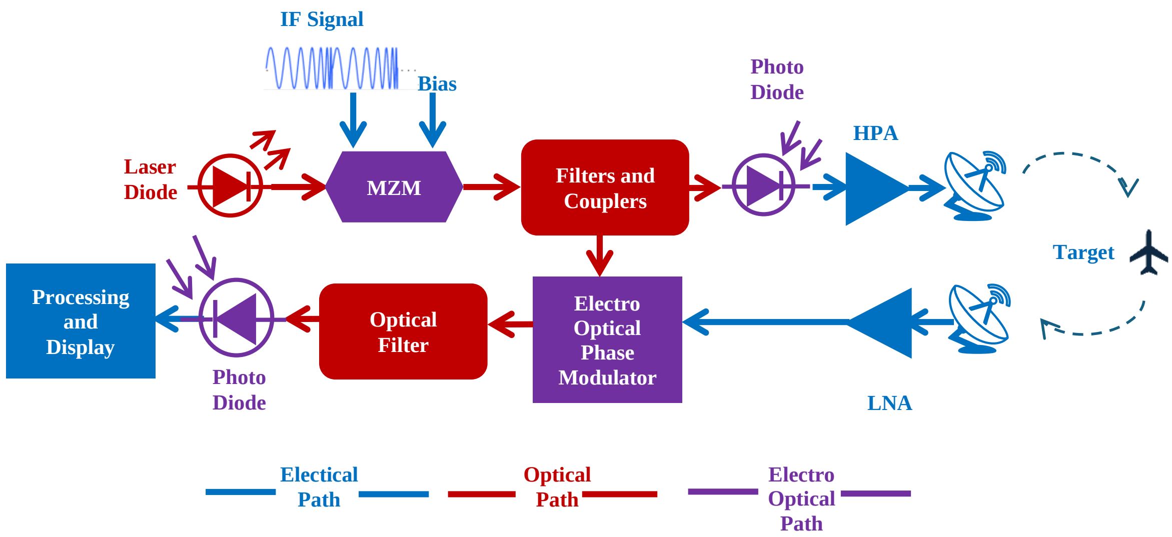

Fig. 11 FMCW based photonics radar

4.3. FMCW-based Photonic Radar Transceiver

An FMCW-based photonic radar is discussed, as depicted in Figure 11, to highlight the radar subsystems. The waveform generated by this scheme, rather than using a voltage-controlled oscillator in the analog domain or digital domain, overcomes the bandwidth problem seen. There are multiple ways in photonic-based generators, of which the dual-parallel MZM-based method is seen in most literature due to the quality and stability of the generated waveforms, which are essential for radar with the application of small targets such as drones.

A sawtooth waveform whose slope and time period are dependent on the requirement of the radar modulates a sine wave to produce a Linear Frequency Modulated (LFM) waveform is shown in Figure 12.

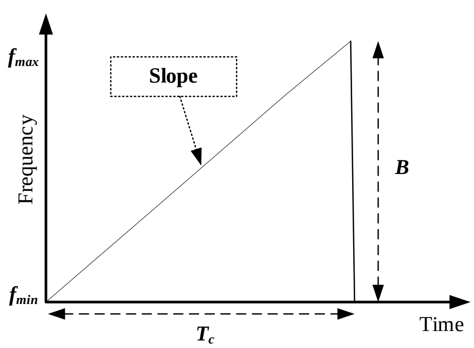

Fig. 3 Up sweep triangular wave showing the Bandwidth *B*, Chirp duration T_s and slope

The linear swept frequency IF waveform is given to the MZM, and the output is taken to the PD for electrical conversion. Another part of the signal is used as a reference in the receiver. The waveform is subsequently amplified and transmitted.

The parameters of the FMCW radar can be found from the various relations between them. The transmitted signal frequency is

$$f_T(t) = f_0 + \frac{Bt}{T_c} \tag{9}$$

f_0 is the starting frequency, B is the bandwidth, and T_c is the chirp duration. The received signal is

$$f_R(t) = f_0 + \frac{B(t-\tau)}{T_c} \tag{10}$$

The beat frequency is calculated by sending the transmitter and receiver wave into a mixer and passing the difference through a lowpass filter. The beat frequency is also related to the round-trip delay and bandwidth B and the chirp duration T_c.

$$f_b = |f_T(t) - f_R(t)| = \frac{B\tau}{T_c} = \frac{2BR}{cT_c} \tag{11}$$

When the target is moving, the beat frequency will have an addition of frequency due to the doppler effect. The effect is addition and given as

$$f_{bmax} = \frac{2BR_{max}}{cT_c} + \frac{2}{\lambda}V_{max} \tag{12}$$

The range can be calculated by,

$$R = \frac{c * f_b}{\left(2 * \frac{B}{T_c}\right)} \tag{13}$$

It has to be noted that the range resolution is dependent on bandwidth, and it is given by,

$$R_{res} = \frac{c}{2B} \tag{14}$$

Authors in [40] presented a conceptual reconfigurable photonics radar citing the difficulty of having multiple microwave components to achieve multiband (narrow and wide band signal process simultaneously) operation. They also point out the existing literature on the photonic generation of linearly chirped radar waveforms, overcoming the limits in bandwidth requirement and jitter. They have shown that all optical up and down conversion, tailored bandwidth, and coherent operation can be performed using a photonics-based system. They have used MLL for generation and reception by which coherence is maintained. The received signal is time-stretched, which leads to frequency compression and allows the existing ADC to operate with ease. The radar is tested with signals in the X band on two metal plates as targets. Even though the experimental setup does not consider real-world situations, the results prove that time-stretched reception does not affect the detection ability. The research proposes a photonic exchange network that enables the selection of antenna elements from the array for narrow or wideband operation. This reduces the number of local oscillators and mixers needed when done electronically.

Dan Zhu D. Zhu, W. Chen [41] has designed a reconfigurable photonics system for the RF front end operating in S to Ka-band. Free Spectral Range (FSR) of 31 GHz and 25 GHz are generated by dual Optical Frequency Combs (OFCs). The generated signal is sent to MZM along with the electrical signal. The received signal, which is in the S-band, is down-converted to the Ka-band optically. The reconfigurability is achieved by selecting the required band in the OFCs. An electrical baseband LFM signal with a bandwidth of 100 MHz and a center frequency of 1.5 GHz was upconverted to various RF bands from S, K, Ku and Ka bands by changing the configuration.

Atsushi Kanno et al. [42] demonstrated a handheld FMCW photonics-based radar operating at 94 GHz with 2 GHz bandwidth for non-destructive testing and identification of concealed targets in short range. The range resolution was 10 cm as opposed to 7.5 cm, as calculated by theory. The research proposes to use super-resolution techniques. Bindong Gao Fangzheng Zhang [43] demonstrated that LFM-based multiband radar operates simultaneously at K bands (19-22 GHz) and Ka bands (34-37 GHz). The spectrum of generated and received signals was obtained, thereby exhibiting the feasibility of a radar operating with less complexity in the frequency K and Ka bands.

V. Sharma and L. Kumar [44] discuss the phonics radar for autonomous vehicles, highlighting the high range-speed resolution and extended tracking range when compared to conventional radar. They have used FMCW-based moving radar at 77 GHz on multiple complex moving targets such as cars, trucks, pedestrians and a bicycle under atmospheric conditions. The targets at the maximum range of 500m were classified by the RCS they produced, and the range and velocity were measured simultaneously. This research has taken adverse weather conditions and their effect on the radar. The better performance of photonics-based radar in these conditions compared to conventional radar is demonstrated. Similar work by Vishal Sharma [44] is about a photonics-based FMCW radar using 77 MHz for multiple targets such as buses, cars and motorbikes travelling at 80, 96 and 60 km/h at a distance of 390, 300 and 100 meters from a moving radar at speed 100km/hr. The main objective of this research was to demonstrate the effect of rain and fog on the intensity of the beat signal. It was concluded that intensity loss is around 20 dBm/Hz.

J. Tebart, M. Steeg and A. Stöhr [45] proposed an FMCW photonics radar operating in the frequency range of 24 GHz to 33 GHz with a bandwidth of 9.35 GHz. The system relies on the 5G network, where there is optical connectivity. The system uses beam angle with respect to the frequency sweep realized by a set of leaky wave antennae. The frequency-time sweep is converted to an angle sweep over time, thereby simplifying the polar localization technique. A 260 % range improvement is realized with a relative error of 0.33% for the targets up to 650 cm range when compared to previous similar research.

Abhishek Sharma [46] et al. used Optisystem® software to realize an FMCW photonics radar for autonomous vehicles under adverse weather conditions up to a target range of 750 m using 77 GHz signals with a bandwidth of 600 MHz. The target was a static object, and the research clearly points out the extension with multiple moving targets using this system.

Sushank Chaudhary [47] extended the above work with moving targets at 41 m/s speed. The impact of sweep time and weather conditions on the target range is provided. The work has taken a range up to 6000 m.

D Liang et al. [48] proposed a multifunctional radar capable of measuring distance, velocity and high-resolution ISAR imaging with the advantage of using a single chirped LFM signal (from 8.5 to 12.5 GHz leading to 4 GHz bandwidth) instead of two. They added a single-tone microwave signal (8 GHz) to get this advantage and showed an absolute measurement error of less than 5.9 cm and radial velocity error of less than 2.8 cm/s with an additional high-resolution ISAR imaging. Three cuboids and one smaller cylinder are the four targets.

4.4. Stepped Frequency Continuous Wave Photonics Radars

The usable range of continuous wave radar is low, and it can be increased by using a stepped frequency wave instead of a continuous sine wave. A CW radar maximum unambiguous range is $R_{max} = c/2f_0$, and for SFCW radar, it is $c/2(f_1$-$f_2)$ where

c is the speed of the light, f_0 is the CW wave frequency and (f_1-f_2) is the step size of SFCW signal. The main advantage of SFCW is the higher SNR values when compared to its CW counterpart. The disadvantage is it cannot detect fast-moving, long-range targets. That is the reason the applications are limited to short ranges. The disadvantage is due to the usage of iFFT (which is also dependent on the Doppler shift produced by the moving targets) when finding the range. Compensation for this shift can be done using various algorithms. A large bandwidth SFCW radar will give good range resolution. The coherence among the sinusoids used in SFCW will provide noise reduction which will enhance differential phase estimation. A multiband operation will be added as a choice, which can allow the user to tune to the best band [49]. SFCW radar, with high bandwidth and the capability to operate at a wide range of high frequencies, faces the challenges posed by electronics and can be overcome very easily with photonics techniques.

One important Stepped Frequency Photonics Radar is in radar interferometry. The interferometric technique is used to find the displacement by phase information of the transmitted signals and received signals at different times. The monitoring area can be large or small based on the applications. Radio interferometry can be air, space-based or ground-based. Ground based systems are well suited to detect tiny movements in a target such as a building or small mountainous area, helping in structured deformities and landslide information. In a fixed time (step interval), a series of time-domain sinusoidal signals with different frequencies(with a frequency separation called frequency step) are generated and transmitted. Several step intervals are used for target acquisition. The received signal from backscattering is mixed with the reference signal (transmitted signal) to obtain the phase information, which is converted to displacement information. It can now be seen that phase noise and coherency in signal generation are important aspects to be looked upon, which will be taken care of in the photonics-based system. The first work on such a system was demonstrated in [49] and extended in [50] for multiband operation in the presence of multiple scatterers. S Pinna et al. [49] used SFCW photonics radar ability to produce stable multiband frequencies to detect sub-mm displacements in lands prone to landslides. They showed that such usage can reduce size, cost, weight, and complexity while avoiding correction algorithms otherwise needed. The radar system was able to measure with measurement error lower than < 200 μm for targets over a range of up to 3 km without correction algorithms. In this extension, the authors used S and X bands. The advantage of using the dual-band radar can be seen in the following equations and arguments.

Let f_0 be the carrier frequency (S or X band) of the waveform generated. The m^{th} sinusoid can be given by the Equation (15)

$$f_m = f_0 + (m-1)\Delta f \tag{15}$$

Where m varies from 1,2,3...N_{Step} giving rise to bandwidth $BW = N_{Step}\Delta f$ which gives the range resolution as per (16)

$$\Delta R = \frac{c}{2BW} \tag{16}$$

If the radar transmits at t_0 and is received at $t_0 + \tau$, the received signal will have the phase of

$$\Phi_m = 2\pi f_m \tau = 2\pi f_m \frac{2d}{c} \tag{17}$$

If two consecutive signals are taken and compared, if there is a change in the target distance, it will be given by

$$\Delta d_m = \frac{c}{4\pi f_m}\Delta\Phi_m \tag{18}$$

The displacement ambiguities are seen when the change in phase is more than 2π, and the unambiguous range is now given as

$$R_{ua} = \frac{c}{2\Delta_f} \tag{19}$$

From the above Equation, we see that Δf plays an important role. If it is increased, the displacement measurement precision increases, but the unambiguous range decreases. Differential phase measurements between the bands in dual-band radar are measured. Large Δf allows the detection of displacements much smaller than a fraction of a millimeter. This research gives additional applications of photonics in radar engineering.

Cong Ma et al. [51] have demonstrated a photonics radar with a frequency-stepped chirp signal instead of an LFM signal with a bandwidth of 18.2 GHz using frequencies from 16.9 GHz to 35.1 GHz, resulting in the anti-interference system capable of providing 8.5 mm x 8.3 mm resolution in 2D imaging. Such a resolution could be achieved by LFM signals with 15 GHz bandwidth but with unwanted harmonics, which could be removed by filters, leading to degradation in SNR. There is also a possibility of interference from other communication systems as well.

Frequency-stepped chirp signal solves the above two problems. Two metallic plane targets (2 cm × 2 cm) spaced 8.5 mm are used as targets. In Liu, Y., Zhang, Z., and Burla [52], photonic stepped frequency is generated progressively, leading to a high accumulated bandwidth. In demodulation, the signal is converted into MHz bandwidth, which is another advantage due to fast processing.

This is opposed to the initial signal, which is usually generated by Arbitrary Waveform Generators (AWG) or tunable high-frequency oscillators, which are expensive. The photonics radar designed in this way used targets as three cylindrical objects (top view) with a radius of 3 cm and a height of 4 cm placed on a rotating platform at 1.5 m.

4.5. Photonics Array Radars

Photonics technologies, with their superiority over electronic-only technology, again help in phased array antenna-based radars. Phased array antenna radar has advantages over single element antenna with its flexibility, increased range and angular resolution. A phased array antenna has, for example, N antenna elements along with individual phase shifters separated by a distance d. A photonics-based phased array antenna system is shown in Figure 13. The beam of this antenna, when steered to an angle theta, should satisfy $\Delta R = d sin\theta$ where ΔR is the minimum distance from the wavefront to the antenna. In the process of generating a beam where antennas have the same phase shift, the adjacent antenna should be shifted by a phase difference of $d\emptyset = \frac{2\pi f \Delta R}{c}$ Where the f is the frequency of operation.

Electronic phase shifters are expensive and non-uniform responses along a large spectrum [2]. Usually, when broadband signals are used, phase shifters cause beam squinting at different frequencies of the signal spectrum to aim at different angles. The advantages of a large bandwidth of ~50 GHz, true-time delay by optical delay line leads to low loss in the orders of four and immunity towards electromagnetic interferences make photonic-based systems attractive[2]. Optical tunable TTDs can be achieved by optical path switching, i.e., sending signals through different lengths so that different propagation time is achieved. A piece of optical fiber with discrete Bragg Gratings is used as a delay unit. Different wavelengths of signals are obtained from different physical points of the Fiber Bragg-grating-based reference delay unit. With this approach, the reflection points can be designed with respect to the needed delays in one single piece of fiber [53]. Other methods of doing the job can be done by variable-propagation-velocity lines based on optical filters or dispersive optical fibers, as seen in detail at [38].

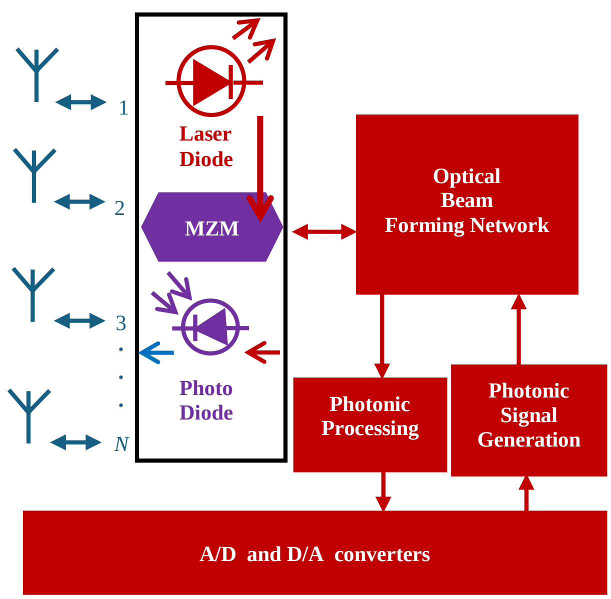

Fig. 13 Photonics array radar

Analog beamforming networks and their digital counterparts, called active electronically scanned arrays (AESA), are used in various implementations [53]. Coherent pulse Doppler AESA radar capable of scanning in azimuth and elevation electronically was designed and tested for 64 antenna elements. In this work, the distribution of RF and digital signals was done by optical systems. The system designed was not used on targets but studied various parameters of the radar such as modularity, remote operation, EMI and nonlinear distortion [53]. In [54], another digital implementation is done for imaging radar and the photonics-based beam forming using variable-length fiber. A single pulse is transmitted by an omnidirectional antenna and received by four number of antenna arrays. The received signal is the summation of four optically modulated, propagated through different length optical fiber signals. The experimental setup was done for a range of four meters and the targets were of size of centimeters.

Fangzheng Zhang et al. F. Zhang, E. Zhao, B. Gao [55], while exploring photonics rad, cites that the limitation of the angular resolution is still an issue. They propose a photonic-based array radar with a 2D MUltiple SIgnal Classification (MUSIC) algorithm for increasing the angular resolution. A bandwidth of 4 GHz using signals of frequency 22-26 GHz on a 1 x 4 phased array antenna. It has to be noted that each receiving element of the array needs individual signal processing systems. They were able to achieve a resolution of 2.68 degrees without the MUSIC algorithm. The target was a plate of size 6 cm x 7 cm at 2.1 meters.

In the previous research, the cross-range resolution of multiple targets moving at close distances was improved by the 2D MUSIC algorithm.

4.6. MIMO Photonic Radar

Photonics-based single-antenna radars and array antennas have already been discussed in previous sections of this work. It was found that difficulties faced in electronics are overcome only by single antenna radar or array antenna radar. Multi Input Multi Output (MIMO) technologies are ripe in the field of communications and are used in many applications, from cellular communications to wireless broadband internet services. The main attraction of MIMO radar is its ability to have high azimuth resolution with improved target positioning and parameter estimation [56]. Additional applications of MIMO Photonics radar include 3D imaging, accurate target position estimation, an increase in detection range with enhanced visibility during disturbances like rain and fog, automotive with better fine-range and cross-range resolutions, multi-target surveillance, maritime surveillance, etc. It has to be noted that MIMO radars will need more computing and storage hardware. A simple block diagrammatic representation of photonics MIMO radar is given in Figure 14. Higher angular resolution is provided by the MIMO radar, where high-angle resolution is needed for the precise location of small targets. Aerial targets, when sensed by advanced three-dimensional radar, broadband operation and large 2D aperture requirement, are satisfied by photonics-aided systems; in a 4x4 MIMO radar that was used on an aircraft, a high-resolution 3D image was acquired, which was shown to be better than electronic-only radar [57]. F. Scotti et al. [58] first demonstrated dual band coherent photonics based on 2 x 2 MIMO radar for short distances. They have extended the work with multiple bands, covering a larger geographical area (5 Km wide shoreline) and improving the RF front end for smaller targets in a sea. The main takeaway from this work is about sidelobe issues when multiple antennas are used and reduced by using multiple bands.

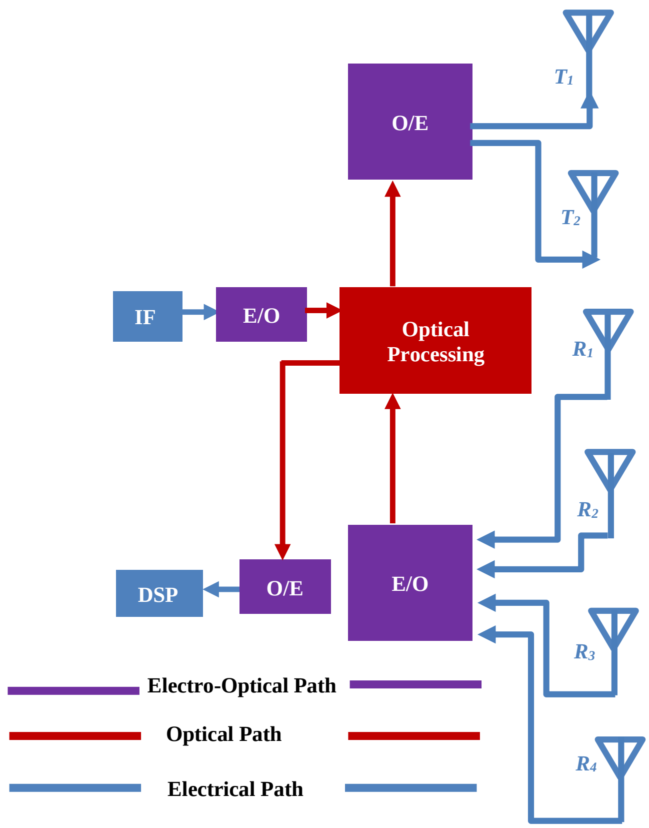

Fig. 4 Photonics based MIMO radar

Angle resolution is needed for many applications where multiple receiver antennas can improve the same. A four-receiver radar (as shown in Figure 14) can have an angular resolution of 30^0 and can be reduced to 15^0 when receiver antennas are doubled. It is not economical to increase the number of receiving antennas, and MIMO technology can ease the burden. As an example, a two-antenna receiver will receive the incident signal in different phases as there is a distance between two antennas. $\omega = \frac{2\pi}{\lambda} dsin(\theta)$ and $\theta = sin^{-1}\left(\frac{\omega\lambda}{2\pi d}\right)$. If $d = \frac{\lambda}{2}$ and increasing antennas will have a linear progression of phase of the received signal seen at each antenna. The received signal is performed FFT, and the peak of the iFFT becomes harper as there is an increase in the river antenna, leading to better resolution. For four antennas and when $= \frac{\lambda}{2}$, the received signals will have phases 0, ω, 2 ω and 4 ω. If an additional transmit antenna is placed at $4d$, the phases will be [0 ω 2ω 3ω] and [4ω 5ω 6ω 7ω], i.e. 1 x 8 = 2 x 4.

Fang Zheng Zhang et al. [56] have taken photonics radar to a new level by using MIMO techniques with a bandwidth of 4 GHz for high-resolution ranging using broadband LFM signals. The signal is generated by photonic frequency quadrupling, as seen in the previous work discussed, and the received signal is dechirped by photonic frequency mixing [59]. The paper discusses their previous work on monostatic radar using the above technology with 12 GHz bandwidth to get a range resolution of 1.3 cm [60] and used a target with the dimension of 2 cm × 2 cm when 2D imaging is used. The authors were the first to demonstrate MIMO radar design, citing the ability of MIMO radars to have high azimuth resolution, Direction of Arrival (DOA) estimation and multiple target tracking. Multiple (equal to the number of transmitter-receiver antennas – 2 x 2 in this case) Orthogonal (guarantees frequency overlapping) LFM signals are transmitted and received at a 4 GHz bandwidth and 100 msps sampling rate in the receiver. A DPMZM modulator was used with light from a laser diode (different wavelengths for different signals) as one input and an intermediate frequency LFM signal as a modulating signal. The wavelength division multiplexing-based combined signal is amplified and split into two, where one signal goes to the transmitter and the other to the receiver array. It has to be noted that two transmitted signals are received by each receiver. The intended signal is separated and processed. The target was rectangular plates of dimensions in centimeters and in the range of hundreds of centimeters. Using the spectrum of signals S_{11}, S_{12}, S_{21}, and S_{22} (for example, S_{12} is the signal from transmitter antenna 1 to receiver antenna 2), the range and DOA are estimated. High complexity and cost are the constraints for this system.

MIMO Photonics radar, when used for automotive applications, can bring benefits in terms of high-range resolution as they can generate and operate very high bandwidth in orders of 10 GHz and use multiple antennas for cross-range resolution along with more degrees of freedom when compared with phased array antenna [61]. In two scenarios, the MIMO radar is placed on the ground, and the other is placed on the car. The targets are a pedestrian and a car. The frequencies used are similar to those presently used, such as 24 GHz and 77 GHz. The accurate localization and identification depends on a log-likelihood function defined and it in turn depends on side peaks around the effective position of the target in cross-range. The calculated parameter for this function is the Peak-to-Side-Lobe Ratio (PSLR), which has to be higher for better results. The simulation changed the number of transmitting and receiving antennas and bandwidth. The observation pointed out that increasing the antenna elements number upto 5 has significantly improved PSLR but reduced it after increasing it to more than 6. It is also observed that an increase in bandwidth has increased the PSLR [61].

Giovanni Serafino et al. [62] summarized the status of photon-based research and the outputs of their previous research on dual-band photonics radar. The paper also extends the need for photonic radar, mainly by using bands that are unused. The MIMO concept is also explained where cross-range resolution is improved by this concept. This research highlights the challenges in the area of high data links between antennas and central processing units and high synchronization in timing and phase coherence, which cannot be satisfied by the present RF technology.

Conventional MIMO radar and photonics-based MIMO radar are compared for a scenario where there are five targets without noise and with noise. In no noise conditions, the resolution with MIMO was tenfold increased, and with noise, photonics-based MIMO radar performed better than conventional MIMO. The whole experiment was simulated.

Another approach taken by S. Maresca et al. [63] is 2 x 2 MIMO photonics radar, where the transmitters can be placed at different places (20 m apart) and connected via optical cable for high bandwidth and high coherence between transmitted and received signals. A 100 MHz bandwidth working at 9.7 GHz with an LFM chirp signal was used. The targets were metallic cylinders of 17 cm radius and 50 cm height, hanging from two drones at a height of 18 m at a distance of 3 m. The superiority of MIMO coherent processing is demonstrated with a monostatic radar. The work was done on scaled geometry but simulated for 1 kilometer. It has to be noted that the target is not the drone but the cylinder hanging from the drone.

Data collected by Coherent MIMO radars increases the detection and localization capabilities. The data is spatially distributed, and exploiting this information can increase the cross-range resolution of a radar. In [64], a coherent 2 transmitters and 4 receivers MIMO photonics radar operating in dual-band Frequency-modulated continuous-wave is proposed. It is shown that cross-range resolution and removal of false targets are done properly when more bands are used.

Vishal Sharma, Hani J. Kbashi and Sergey Sergeyev [65] extended the Vishal Sharma and Love kumar work by introducing 2 x 2 MIMO configuration to the previous work. They have again concentrated their work on the effect of fog and rain. Three-hundred-meter extension of the detectable range is obtained with MIMO when compared to SISO with the help of the spacial diversity introduced by the MIMO scheme. The authors again point out the increased complexity and cost of the system.

Three Dimensional (3-D) imaging radar provides more geometric features than the 2-D counterpart but with the expense of broad operating band and requirement of large apertures. These two parameters are enhanced with the help of a higher range and angular resolution. In [66], MIMO photonics radar with four TXs and four RXs antennas capable of 3-D imaging is proposed where there is a Central Office (CO) generating and receiving signals and processing them. The photonics signals are transmitted to the antenna by optical cables, and received signals from the antenna are converted to optical signals and sent back to the receiver in the CO. The transmitters and receivers, in this case, do the Electrical to Optical conversion and vice versa. The target used in the field test was boing B777 at the range of nearly 1 KM. This research has overcome the trade-off between low system complexity and large 2D apertures.

4.7. ISAR Photonics Radar

Shaowen Peng et al. [67] define the need for wideband radar for its advantages in high reflection of metallic objects, living tissues and high penetration of paper, cloths, smoke and clouds. Electronic Inverse Synthetic Aperture Radar (ISAR) system operated in wideband has phase noise, reduced resolution and poor imaging quality. Two metallic mirrors separated in centimeters and placed at a range of tens of centimeters are used as targets. The research demonstrated an ISAR imaging system of 8 GHz bandwidth and two-dimension (range and cross-range) imaging resolution of ~1.9 cm × ~1.6 cm using photonic technology. In [68], we have designed a photonics-based FMCW radar for high-resolution ISAR imaging. The main contribution is the photonic generation of signal with a bandwidth of 8 GHz at K band (18–26 GHz) and photonic dechirping of the received waveform. By this, the receiver uses a low-speed A/D converter. They have also demonstrated a real non-cooperative LSS target with imaging at 25 fps. Deng et al. [69]designed LFM pulse radar for ISAR imaging with a photonic A/D converter. A very high bandwidth of 8 GHz (leading to high imaging resolution) centered around 36 GHz was directly sampled. This research points out the detection range swath limitation when FMCW radar is used and photonics de chirping. Models of Plane, UAV, and Y20 were used to collect ISAR images in various postures. They were then used to train a CNN, and from there, classification was done at an accuracy of 95%.

Wangzhe Li et al., W. Li, R. Li, J. Dong, and J. Yang [70] demonstrated a vehicle-mounted photonics radar with a 2D resolution of 3 cm (range direction) and 4 cm (cross-range direction). The radar operates at the Ku band with 5 GHz bandwidth and uses an LFM signal in the transmission and stretch processing in the receiver. The research highlights the importance of the need for higher carrier frequency and bandwidth for an increase in the resolution of Synthetic Aperture Radars (SAR). SAR and inverse SAR imaging are used with 6 trihedral corner reflectors as targets in the ground.

4.8. Hyrid Photonics Radar

Nie H et al. [71] proposed a photonics radar that can also act as a communication system. Even though such a system was demonstrated earlier [23, 72], this system uses the same frequency band for a dual purpose. The system in [72] had 54 Gbps 64-QAM OFDM reception and detection and velocity measurement of a moving target. S. De and A. A. B. Raj [11] were able to use Optisystem® to implement a photonics radar operating in multiband and use Matlab® as an additional tool. This research has shown that available software tools can be used to implement and test photonics-based radar.

5. Requirements for Photonics-Based Radar for Complex Targets

Complex targets such as LSS targets need higher bandwidth of operation and lower phase noise. Photonics technology can be used to solve the bottlenecks posed by classical radars. For example, a drone is a complex small target that has the capability of doing more serious damage in future warfare. Such targets are smaller in size and comparable to the sizes of birds. Therefore, more than detection, classification of the target is important. The flipping of a bird's wings and the rotation of blades of rotors are different, and to capture this phenomenon, signals with ultra-phase stability are needed. Micro Doppler analysis is additionally needed for target discrimination. In this case, multiple radars are to be used: one for surveillance and the other for classification. The drones use composite materials, and one band may not be suitable for multiple types of drones. In this case again, Electro Magnetic Interference (EMI) from mutual coupling from different bands and support of cable for all radars are not possible. A photonics radar, which does most of the processing in the optical domain, is preferable. Higher imaging resolution, ultra-high range resolution, higher azimuth resolution, Direction of Arrival (DOA) estimation, multiple target tracking, higher angular resolution and special resolution are needed for drones or swamp of drones as a target. A Table showing the present State-Of-The-Art photonics technology-based radars and the targets involved.

Table 1. Summary on photonics radars for target detection

Reference	Radar type/Band/BW	Range	Target	Notes
[73]	Pulse/X/ 300 MHz	5.4 km	Aircraft	High power 20 W, Summary of advantages and necessity of photonics-based radars. Detection only.
[39]	Pulse/S&X/ 200MHz	3.8 km	Aircraft	X band gave higher Doppler estimation, and the S-band was immune to weather conditions. Detection of range and velocity only.
[38]	Pulse/X&S/ 200MHz	3 NM	Boat	High power 50W. Multiband operation and fusion of data from two bands. X-band radar has better velocity resolution than S-band radar.
[40]	Pulse Radar/X/ 4GHz	80 cm	Two metal plates	Demonstration of all-optical up and down conversion, tailored bandwidth, and coherent operation
[59]	Pulse Radar/K/ 8GHz	3.5 m	Two metal plates	The research shows the ability of photonics to generate very high bandwidth.
[42]	FMCW/W/ 2GHz	6 m	-	Handheld operation and has applications for health monitoring and inspections of ancient arts.
[43]	FMCW/K&Ka/ 3GHz	-	Delay produced by an electrical cable	Multiband radar with a simple structure and good flexibility.
[56]	Pulse/K/ 4GHz	160.9 cm	Metallic plane target with a size of about 6 cm × 4 cm	Combination of multiple orthogonal LFM signals using WDM. Only target detection.
[70]	FMCW/Ku/ 5GHz	3 and 5 cm	6 trihedral corner reflectors as targets in a ground	ISAR image is captured.
[44]	FMCW/W/ 600MHz	500 m	Automobiles	The better performance in adverse weather conditions by photonics-based radar compared to conventional radar is demonstrated.
[58]	FMCW/S&X/	3 km	Emulated target.	2 x 2 MIMO radar sidelobes issues when multiple antennas used are reduced by using multiple bands

[46]	FMCW/W/ 600MHz	750 m	Static emulated target	Optisystem® is used in this research
[47]	FMCW/W/ 600MHz	6000 m	Car	Impact on sweep time and weather conditions
[48]	FMCW/X/ 4GHz	~2 m	Three cuboids and one smaller cylinder	Multifunctional radar capable of measuring distance, velocity and high-resolution ISAR imaging
[74]	FMCW/X/ 5 & 2.5 GHz	2.7 detection and 1.1 km image acquisition	Matrice 600 Drone	Field demonstration performed.
[63]	FMCW_MIMO/X/ 100 MHz	3 m	Metallic cylinder in centimeters hanging from two drones	The advantages of coherent MIMO processing demonstrated.
[65]	FMCW_MIMO/W/ 600MHz	500 m	Car, Truck, Motorbike, Bus, Pedestrian	Three-hundred-meter extension of the detectable range is obtained with MIMO when compared to SISO with the help of the spacial diversity introduced by the MIMO scheme.
[66]	Pulse_MIMO/X/ 2GHz	1 kilometers	Boeing B777	3D resolution, cross-fertilization between microwave photonics and radar arrays.
[51]	SFCW/Ku – Ka/ 18.2 GHz	1 meters	Two metallic plane targets (2 cm × 2 cm) spaced 8.5 mm	Range resolution in CMs is targeted.
[52]	SFCW /Ka/ 11.52GHz	1.5 meters	Three cylindrical objects (top view) with a radius of 3 cm and a height of 4 cm	Range resolution in CMs is targeted.
[68]	FMCW/K band/8 GHz	17 meters	UAV	High-resolution ISAR images and real-time tracking
[69]	Pulse_ISAR/Ka/8 GHz	1.6 meters	Two pyramids	ISAR and high radar imaging resolution. Application of photonic A/D converter.

It is seen from Table 1 that the targets used are larger in size, emulated in some cases, good reflecting objects placed in stationary positions.

Y. Bae, J. Shin, et al. [74] proposed a photonics radar for detecting (up to 2.7 km from radar and has a range resolution of 30 m with 5 MHz bandwidth) and imaging (up to 1.1 km from radar and a range resolution of 0.1 m with 2 GHz bandwidth) a hex copter (with velocity 72 km/h and usually gives low RCS in real time) using 10 GHz signal in X band. This research is one of the first of its kind to use real-world scenarios working for larger distances on a complex target. The receiver also uses a delay interferometer and balanced photodiode to cancel the relative intensity noise.

6. Conclusion

This paper has given an elaborate survey on photonics radar developed for various applications, highlighting the frequencies used, targets studies and various resolutions obtained. Photonics technologies used for achieving various radars discussed are not elaborated on as the scope of the survey was about the applications of photonic radar. Photonics-based radar has advantages over electronic in the area of generating stable signals with low phase noise and higher bandwidth, which is required for high resolution when complex small targets are to be detected. The photonics in the receiver again help in sampling with low jitter and more ease. The above survey clearly promises to use photonics radar with all its advantages without any major constraints for real-time implementation. Coherent radars are preferred for better detection capability but with increased system complexity. Radars with multifunction are needed presently, and reconfigurable receivers are needed where software-defined radio is promising. Again, photonics-based radars can generate and operate at different bands. Literature shows most of the work has been done in the X and S bands, whereas exploring the Ka, V and W bands will be worth it. More work has been done on pulsed radar than on FMCW radar. Most of the research that has been done on photonics-based radar is tested in lab environments with reflecting objects as targets placed at a short range without complex movements. It is also seen that real world targets and outdoor experimentation of the research are not usually done in many research. The paper also shows that moving complex small targets detection is one such field that will benefit from photonics technology in radar.

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