

# Simulative Investigation of FMCW Based Photonics Radar Modelling

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**Abstract**—The paper presents the main objective of FMCW based photonics radar and target detection. The real time distance measurement, target recognition, Doppler shift frequency measurement, target's velocity, angle of arrival measurements is the area of studies by the engineer and researcher. In the near past, development of photonics radar is very complex. Its interference with the electromagnetic wave is very low as it works in the wide band. Before the hardware photonics radar setup, the ground work for modeling and simulation is necessary. In this project, FMCW photonics radar was designed in MATLAB.

**Index Terms**—ADC, DP-MZM, FMCW, LNA, PD, PM

## I. INTRODUCTION

Photonics radar is a technique by which radar is produced and analysed with the help of photonics rather than traditional RF engineering techniques. The frequency of the radar is still in the RF, but lasers are used to create and analyse the RF signals with high precision. The potential benefits are longer range of detection, better position sensing, and high-resolution target detection. The cross-fertilization between photonics and FMCW systems setting new paradigms in radio technologies, promising improved performance and new applications with strong benefits for communication systems broadly as well as for public safety specifically.

In particular, the use of photonics in radar systems is leading to a new generation system that can manage multiple simultaneous coherent radio signals at different frequencies, thus enabling multispectral-imaging for advanced surveillance. In fact, thanks to its tenability and huge bandwidth, photonics matches the flexibility requirements urgently needed in future software-defined radar architectures. It guarantees better system compactness because a single shared

transceiver can be used for multiband operations with the added potential of photonic integration.

FMCW photonics radar is an advanced technology that merges microwave radar principles with photonics to achieve high-resolution, long-range detection of targets. It was demonstrated that FMCW photonics is an excellent replacement for a conventional radar. Even more, a complete radar system can be built with the addition of optical modulators, beam splitters, photodiodes, lasers, and band-pass filters. Merging all building blocks into a single photonic integrated circuit minimizes the complexity, cost, and power consumption of an entire radar system. Due to the enlarged difficulty of the electronics component for large bandwidth, we had to rely on the delightful photonics system. This paper is aimed to establish the importance of photonics radar and investigates its characteristics.

## II. DESIGN METHODOLOGY

The proposed radar transceiver consists of a laser diode (LD), RF signal, dual-parallel Mach-Zehnder modulator (DP-MZM), optical coupler, phase modulator (PM), photo detector (PD), transmit and receive antennas, amplifier, low noise amplifier (LNA), analog-to-digital converter (ADC), radar signal processing (RSP), and a radar control center (RCC). The photonic elements, such as LD, DP-MZM, and PM are implemented in the proposed FMCW radar transceiver to achieve wideband properties, and these allow us to obtain high-resolution target detection.

In the receiving path, the optical signal split by the optical coupler from transmission is used as a reference for the dechirping process to obtain beat frequency for the FMCW radar transceiver system.

The beat signal is obtained by combining the transmitted signal and backscattered signal in the receiving path and the received signal can be used for target detection using digital signal processing (DSP). The proposed transceiver system with photonic elements does not use various electrical elements such as mixers and filters that are used in conventional radar transceiver systems, and consequently it has some advantages like low frequency-dependent loss, wide bandwidth, tunability for operating frequency, and immunity to electromagnetic interference (EMI). Using FMCW photonics radar high resolution target detection can be achieved. Also, Photonics radar modeling offers significant advantages over traditional radar systems including its utilization of light-based signals, enabling more precise measurements and superior performance in complex environments.

### III. EXPERIMENTAL SET UP

#### *A. Principle of Photonics radar*

The main principle of radar is by transmitting electromagnetic (EM) waves towards the target and by receiving the reflected echo signal, the range, velocity and type of the target can be detected. This application needs high radio frequency stability.

A direct digital synthesizer (DDS) generates linear frequency modulated (LFM) signal [7]. This LFM signal is modulated by a laser source. After getting modulated the one bunch of the signal is sent to photodetector for optical to electrical conversion and then send to free space by transmitting antenna. The waveform of the transmitted signal and the operation frequency band can be selected according to the type of target to be detected [8], [9].

When echo signal comes after hitting the target, it gets detected by the receiver antenna, it goes electrical to optical conversion and gets compared with the previous reference signal for the error detection purpose. Then the signal goes through analog to digital converter (ADC) after down conversion of the frequency. After photonics analog to digital conversion, a moderate sampling speed is used for the real time signal processing. There the interface control, sensor signal processing and micro-Doppler extraction takes place [10]. Then, target feature measurement techniques are used in data acquisition system.

The first requirement is to generate RF signal through photonics. For the generation of continuous wave RF signal FMCW laser is required because if pulsed laser is used then the generated RF signal is also in pulsed form. FMCW laser act as an optical signal source for both in the transmission side and at the receiving side of the radar. In this paper, work is carried out on frequency modulated continuous wave photonics radar.

For the generation of both type of RF signal i.e., continuous wave RF signal, the requirement is to modulate the optical signal through low (intermediate) RF signal with the help of electro-optic modulator. Electro-optic modulator work at particular operating point through bias voltage to get the desired RF signal at the photodetector. In almost everywhere in the photonics radar Mach-Zehnder modulator is used. Here the main function of MZM is to mixing of two optical signals at the photodetector. MZM works on particular operating point with the help of bias voltage. If the modulator output optical signal is having very low intensity, then optical amplifier is required. Based on requirement mainly EDFA or Raman amplifier is used. Now the photodetector is used to get required RF signal. For this purpose, generally, PIN photodiode is used due to less noise. Afterwards the RF signal needs to be radiated through antenna in the desired direction to detect the target. But the RF signal amplitude must be higher because in the environment it faces high attenuation. So, it is required to amplify the signal before radiating it from the antenna.

After the signal get radiated in the environment and it get intercepted by the target and reflected back. Then with the help of antenna the reflected signal has to be detected. This received signal requires amplification, RF amplifier is used to amplify the signal. In the photonics radar, the received signal again to be converted to optical signal through electro-optic modulator. The optical signal can be used to signal processing in optical domain like optical sampling which is better for analog to digital conversion of the signal because of low noise and high accuracy.

Further the optical signal is demodulated through photodiode for further processing for calculating range, beat frequency etc. According to the laser source type, the photonics radar can be divided into two types. If a mode locked laser (MLL) is used by type of target to be detected [8], then it is the pulsed photonics radar and if a continuous wave (CW) laser

is used then it is frequency modulated continuous wave (FMCW) photonics radar. The time difference is needed to be measured between transmitted pulse and received pulse for measuring the distance of the target. Though pulsed photonics radar is better for detecting the low radar cross-section (RCS) targets, the main drawback is, it cannot give good range resolution. When more than one targets are close to each other it cannot detect the targets separately [11]. So FMCW photonics radar is taken because of high resolution.

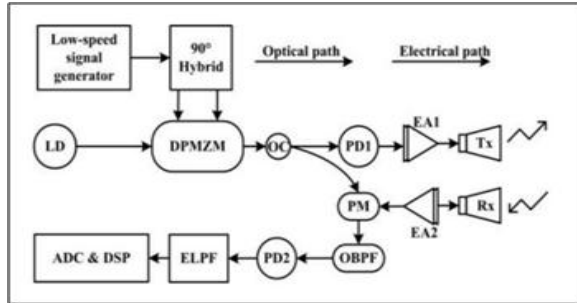


Fig.1. Block Diagram of Photonics Radar

#### IV. FMCW PHOTONICS RADAR SOFTWARE MODELLING

Depending on the types of continuous wave, we can define three types of continuous wave radar. i.e., single frequency continuous wave radar, multiple frequency continuous radar and the frequency modulated continuous wave radar (FMCW) [10]. For the higher accuracy we have used the FMCW photonics radar. In this paper we have made FMCW based photonics radar was designed in MATLAB software. In this platform, we can design any optical telecommunication models which minimizes the time of hardware experimental setup.

First, we generate linear frequency modulated (LFM) signal. One pseudo-random bit sequence gives input to a saw-up pulse generator and the output goes to the electrical frequency modulator. After that generate the LFM signal. Continuous wave laser as the optical input to the system. Mach Zehnder modulator (MZM) as the intensity modulator. According to the Fresnel equation, law of reflection of light calculated, when light wave gets reflected from low refractive medium to high refractive medium it experiences a phase shift while passing through a dielectric medium. Mach-Zehnder modulator has of an input waveguide which is split up into two waveguide interferometer arms and

then they are combined and again become single waveguide. It is the non-linear medium present in the path that allows the electrical field to linearly vary optical fields.

There are mainly two types of Mach- Zehnder Modulator, single drive and dual drive. Here used the dual parallel MZM. The previously generated LFM signal is split in two parts for in-phase and quadrature-phase. In the modulator there will be a frequency mixing of these two phased LFM signal. Next, the RF signal is being modulated by the optical signal in the MZM. The output signal is amplified and passes through the optical fiber. PIN photodiode is used for the photodetector at the end of the optical fiber. Photodiode converts the optical signal to electrical signal. Then the electrical signal is passed through the bandpass Bessel filter and transimpedance amplifier (TIA), that is the front end of the transmitter antenna. Then in the form of radiation it is transmitted to the desired direction.

After getting reflected by the target we got the echo signal and it is again passed through TIA again for voltage to electrical conversion. Then the electrical signal goes to an input of MZM analyser. The same optical input signal used by transmitter is again given as input to the optical port of the MZM analyser. At the output of MZM analyser we get optical signal which is processed for information.

#### V. SIMULATION RESULTS AND ANALYSIS

The range of the radar is determined by the time, T i.e., time taken by the RF signal to travel to the object and travel back to the radar. It is known that Electromagnetic waves travels with the light's speed in free space and the RF signal is also part of electromagnetic waves. So, RF signal travels with speed of light in free space which is,  $C = 3 \times 10^8$  m/s. Generally, Time taken by the signal to go to the object positioned at a range R and coming back to the radar is  $2R/C$ . Thus, range to the target is given as,

$$R = C \cdot T / 2,$$

This equation is known as Radar range equation.

An Antenna gain is denoted by 'G' and it is given by, Gain is equal to maximum power density radiated by a directive antenna / Power density radiated by a lossless isotropic antenna with the same power input. The radar cross section( $\sigma$ ) of the target determines the

power density returned to the radar for a particular power density incident on the target.

$P_r = P_t * G_t * G_r * \sigma * \lambda^2 / (4 * \pi)^3 * R^4$ . This is the radar range equation.

Where,

- $P_r$  = Power of the RF signal which is received
- $P_t$  = Power of the RF signal which is transmitted
- $G_t$  = The gain of the transmitter antenna
- $G_r$  = The gain of the receiver antenna
- $\sigma$  = Radar cross section
- $\lambda$  = working wavelength
- $R$  = range

**A. Transmitter Section**

**1. Time Vs Amplitude Plot**

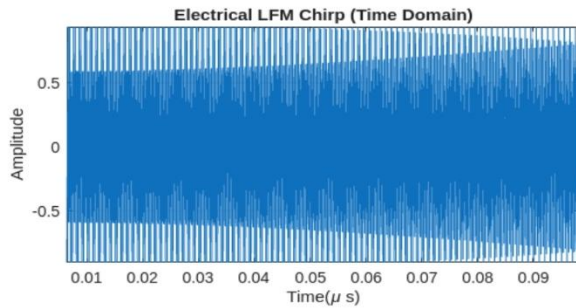


Fig.1. Spectrogram of LFM Chirp

**2. Time Vs Frequency Plot**

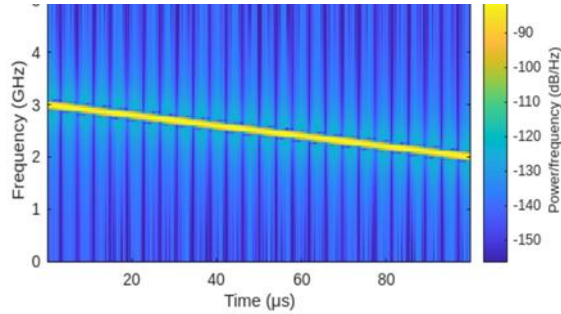


Fig.2. Spectrogram of LFM Chirp

**3. Frequency Vs Magnitude Plot**

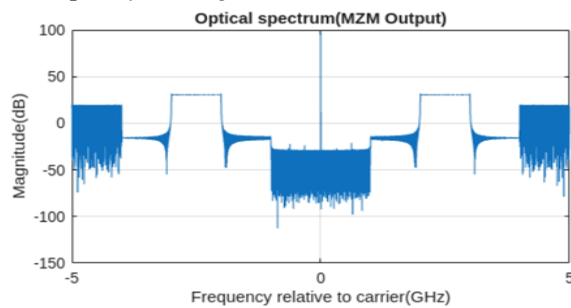


Fig.3. MZM Output

**B. Receiver Section**

**1. Frequency Vs Magnitude Plot**

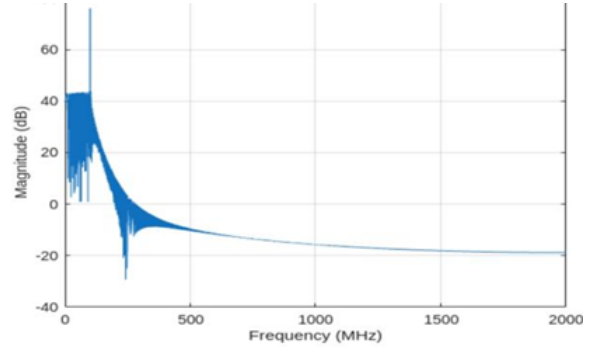


Fig.5. Frequency Spectrum

**2. Range Vs Power Plot**

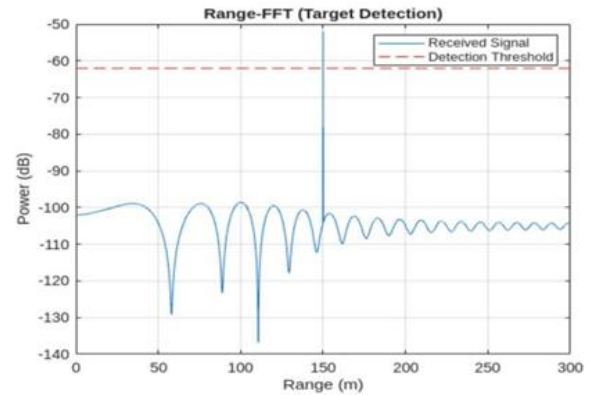


Fig.6. Target Detection

**C. Typical Values used for simulation**

- Speed of light,  $C=3e8$
- Operating Frequency: 20 GHz
- Bandwidth (Bw): 2GHz
- Sweep Time ( $T_m$ ): 100us
- Sweep Slope,  $k$ : B/ $T_m$
- Sampling Rate ( $F_s$ ):  $10e9$  (should be greater than bandwidth)
- Maximum Target Range ( $R_{max}$ ): 750
- Maximum Target Speed ( $V_{max}$ ): 200-300km/h
- Target Radar Cross Section: 1
- Noise Figure: 4.5dB
- Beat frequency,  $F_r = (2RB/T_mC)$ ;  $T_m$  is sweeping time.

**D. Signal to Noise Ratio**

The standard SNR equation is,

$$\left(\frac{S}{N}\right)_{\max} = \frac{E}{N_0} = \frac{P_t \tau G_t G_r \lambda^2 \sigma}{(4\pi)^3 R^4 k T_s L_1}$$

where,

Pt – Transmitter power

Gt, Gr – Transmitter, Receiver gain

$\lambda$  – wavelength

$\sigma$  - Target Radar cross section

R – Target range

k- Boltzmann's constant ( $1.38 \times 10^{-23}$ ) J/K

Ts- System noise temperature

Bn- Noise Bandwidth

Lsys – System Noises Hence,

Simulated SNR=96.95 dB

### E. Resilience

Maintaining high resolution target detection (range and velocity) under adverse conditions such as atmospheric turbulence, fog etc. occurs due to higher bandwidth and lower transmission losses. Factors enhancing resilience are large bandwidth, coherent detection, optical fiber transmission.

### F. Attenuation

Moderate fog approx :28.9dB/km

Heavy Fog/rain :50dB/km

$P_r = (P_{tx} \cdot \sigma_t \cdot (D^2/4R^2) \cdot n \cdot e^{-2\alpha R})$ , Where  $P_{tx}$  is transmitted power,  $D$  is receiver aperture diameter,  $R$  is targeting range,  $\sigma_t$  is target reflectivity,  $e^{-2\alpha R}$  is attenuation term,  $\alpha$  is attenuation coefficient,  $n$  is receiver efficiency. Impact on performance include SNR degradation, range limitation. Key factors are atmospheric condition, fog and rain, visibility, wavelength dependence. To mitigate this use frequency band selection, high power laser sources and coherent detection. Leakage cancellation, equalisation, optimal thresholding, wavelength management in signal processing system.

### G. Sensitivity and Resolution

High sensitivity, often achieving a SNR i.e., 10 times better than conventional electronics-based radar, allowing for the detection of small radar cross section targets, even down to  $0.1 \text{m}^2$ . It means the ability to detect weak signals. Range Resolution= $\Delta R=C/(2B)$ , for closely spaced targets.

A 150 MHz bandwidth provides a 1-meter range resolution, while a 2 GHz bandwidth can achieve a 7.6cm resolution.

Radar Range equation,

$P_r = (P_{tx} \cdot \sigma_t \cdot (D^4/4R^2) \cdot \lambda^2 \cdot e^{-2\alpha R} \cdot n)$ ; for maximum distance. Maximum Unambiguous Range( $R_{max}$ ) Limited by the sampling rate and sweep time.

$R_{max} = ((C \cdot T_m \cdot F_s) / (2 \cdot B))$ , where  $F_s$  is sampling rate.

Range FFT,  $R = ((\text{Beat frequency} \cdot C) / (2 \cdot B))$

## VI. CONCLUSION

This paper simulated the photonics radar at 77GHz frequency. FMCW Radar fundamental equations are used for the simulation purpose. The results represent different parameters as per theory. The reflection part and receiving part is simulated through MATLAB and investigates performance evaluation factors. In future, the results will be used for actual hardware RF and Optical components set up.

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