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Design and Implementation of a Photonic-Based Electronic Warfare System

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Abstract: Nowadays, the radiofrequency (RF) photonics become an inevitable candidate to address several military-related potential applications including electronic warfare (EW), photonic signal processing (PSP), photonic-based RF transportation, and photonic communications. As part of this emerging technology development/requirement, we designed a photonic-based EW system (PEWS) in the optisystem environment (later implemented using optoelectronic components) to extract various radar waveforms such as continuous wave (CW), pulsed wave, and frequency/phase-modulated wave. All these radar waveforms are transmitted and captured by the proposed/implemented PEW system and then processed to construct the radar signatures from its electromagnetic (EM) spectrum/signals. The key parameters of various waveforms generated and processed in our research work are varied, over the time, during the performance validation tests. The values of key parameters of the waveforms, RF CW signal frequencies, pulse repetition time, pulse widths, Barker code phase modulations, Frank code poly-phase modulations, sweep frequencies, and RF power levels are 100 Hz through 8 GHz, 10 ms through 2 μs, 750 ns through 2 ns, 0º/80º, 0º/90º /180º/270º, and −84 dBm through 30 dBm, respectively. The details of PEWS design approaches, their implementation methodologies, and different performance validation experimental results are reported and analyzed. The limitations and possible immediate research contributions/requirements are also listed.

Keywords: photonics electronic warfare system, optisystem simulation environment, continuous wave radar signal, pulse-compressed waveform, frequency-modulated CW signal, phase modulation waveforms, radar signature extractions

1. Introduction

A set of technologies and strategies used to understand the electromagnetic (EM) spectrum/signature for various military potential applications are known as an electronic warfare system (EWS) [1]. EW systems' sensed/detected signals are meant to create and broadcast counter-EM spectrum to protect against enemies. The EWS, at the top-level, is organized into three categories: electronic attack (EA), electronic protection (EP), and electronic support [2, 3]. The EA system uses the EM spectrum/radiation to attack/destroy the enemy systems, such as jamming and directed energy weapon systems [4]. The EP system defends our own and/or friendly electronics (communication/surveillance) systems against the EA of opponents via encryption or EM shielding [5, 6]. The ES system gathers/captures and interprets the key parameters of the radar/communication signals from the captured EM spectrum in order to establish situational awareness [7, 8]. A lengthy and dynamic history of the advancement of electronic technology and military tactics is inextricably linked to the evolution of EW systems. During the World War I [9, 10], the first form of EW system was developed and used in a simple way. Radiofrequency (RF) transmission was used in the war for communication while the radio technology was still in its infancy [10, 11]. During these periods, jamming the enemy RF signals and intercepting their messages became tactical requirements. In World War II [11], the EW system capabilities were relatively advanced with several electronic sophistications. With the development of radar technology, the necessity for radar deception and jamming became essential. In an effort to impede enemy communications and obtain the upper hand in combat, the axis and allied forces both participated in EW operations [9, 11]. During the Cold War, the EW technologies made considerable advances with sophisticated electronics and signal processing techniques/modules [12, 13]. The introduction of more powerful and sophisticated radar systems spurred the development of electronic countermeasures (ECM) and electronic support measures (ESM). While the ESM focused on intercepting and studying opponents' electronic signals, the ECM entailed disrupting hostile radar and communication equipment [14, 15]. In terms of EW, the Vietnam War was a turning point [9, 10]. The United States used a variety of ECMs to damage North Vietnamese air defense systems, including radar jamming and suppression of enemy air defenses tactics [10]. This conflict demonstrated the significance of EW in modern aircraft combat as well. The incorporation of computer technology in the EW systems resulted in increasingly more powerful systems during the late 20th and early 21st centuries. The EW currently encompasses not only the radar jamming and communication disruption but also the cyber warfare, electronic intelligence (ELINT), and EA capabilities [16, 17]. The intelligent way of interception and

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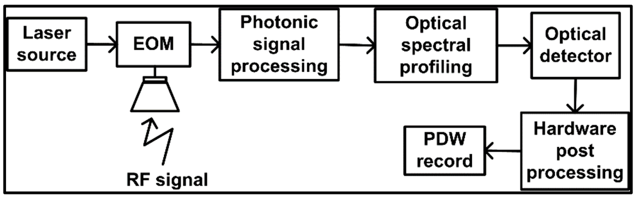
Figure 1
Top-level schematic of photonic-based electronic warfare (EW) system



analysis of electronic signals is referred to as ELINT, whereas the use of EM radiation to target the adversary systems is referred to as EA [18, 19]. As the technology advances, the EW systems grow more advanced and integrated with other military capabilities/ appliances. In order to combat opponents in the air, land, sea, space, and cyberspace, the modern EW systems are built to function in the contested and complicated EM environments [20, 21]. The EW has progressed from simple radio jamming to highly complex and integrated systems that play a critical role in modern military operations, allowing forces to gain a significant advantage over adversaries by disrupting their electronic systems and communication networks [22–24].

As technology has advanced and been used in military applications, photonics integration into EW systems, as shown in Figure 1, has changed throughout the time. Using the photons (i.e., light wave), it is possible to capture/transmit/process a wide-/ multiband (up to mm EM wave) RF signals across long distances via optical fiber for the purpose of EW applications such as extraction of signatures/key parameters of radar systems, communications signals, and other EM applications [25–27]. As shown in Figure 1, the multiband (e.g., DC-40 GHz) instantaneous bandwidth RF signals of different types/modulations are captured by a suitable antenna that pumps the received signal into the optical carrier signal (generated by an optical source) via an electro-optic modulator which is then processed in optical domain (therefore no bandwidth limitations), and then, the spectral profiling is also done in the optical domain. The optically processed RF signal is constructed back into electrical domain/ signal, by a large-bandwidth photodiode, i.e., optical detector, which is subjected to hardware post-processing, as shown in Figure 1, and subsequently into the pulse descriptor word (PDW) record generation. When compared to the traditional metallic conductors, photonics-based devices carry data with far reduced signal loss and experience little to no EM interference (EMI) when traveling through the fiber [28–31].

Therefore, nowadays, the photonic-supported EW system is one of the critical and emerging worldwide research requirement [32, 33]. Table 1 gives precise comparison between EW system (EWS) and photonic-based EWS (PEWS) in terms of certain critical factors [34–36] such as signal transmission, communication medium, speed of signal transmission, security, size and weight, frequency range, signal processing, sensitivity and resolution, interference and crosstalk, adaptability, and environmental factors. With the advent of laser technology, photonics made its first entry into EW technology in the year of 1960s and to a greater level in the year of 1980s. Lasers were used in this era mainly for communication, target identification, and range finding [37]. Fiber-optic technology advancements at the same time provided benefits for security and signal integrity. Photonics technology is found useful in optical countermeasure systems, especially in laser countermeasures intended to interfere with or neutralize missile sensors and seekers [5, 38]. Photonics was recognized as a critical instrument for modifying EM signals in a wartime environment during this period. These systems significantly contributed to improve the situational awareness and safeguarding platforms against EM attacks. In the 21st century, optical technologies were significantly incorporated into RF systems known as RF photonics, marking a significant advancements [9, 39]. This included the use of photonic components in EW applications for signal processing, wideband communication, and frequency measurement. The goal of

Table 1
A comparative analysis of EW and PEW systems

Features	EWS	PEWS
Signal transmission	Utilizes electrical signals (electrons)	Utilizes optical signals (photons)
Communication medium	Typically relies on copper cables and RF components	Utilizes optical fibers and photonic devices
Speed of signal transmission	Limited by the speed of electrons	Higher speed due to the speed of light in fiber optics
Security	Vulnerable to EMI	More secure due to reduced EMI and susceptibility
Size and weight	Components may be bulkier and heavier	Smaller and lighter components due to the compact nature of photonics
Frequency range	Limited by the characteristics of electronic components	Broader frequency range, especially in RF photonics
Signal processing	Uses electronic circuits for signal processing	Use of photonic devices for signal processing, offering advantages such as low loss and high bandwidth
Sensitivity and resolution	Limited by the characteristics of electronic components	Higher sensitivity and resolution, especially in radar/communication signals
Interference and crosstalk	Susceptible to EMI and crosstalk	Reduced susceptibility to EMI, and potentially lower crosstalk
Adaptability	May require additional components for adaptability	More adaptable due to the flexibility of photonic components
Environmental factors	Susceptible to EMI, temperature variations, etc.,	More robust in challenging environments, potentially less affected by EMI

ongoing research and development is to improve overall performance by integrating photonics into EW sensors. Detecting, analyzing, and tapping countermeasure systems into place involve the use of RF photonic technologies [13, 40]. Looking ahead, the future of photonics in EW is anticipated to feature advancements in integrated photonics, providing compact and efficient solutions for multifunctional systems. Photonics is poised to maintain its crucial role in addressing the challenges posed by congested EM environments and in augmenting the adaptability of EW systems. Addressing these research requirements to a possible greater extent is the main research contribution presented in this paper.

The rest of the paper is organized as follows: Section 2 briefs the principles of radar waveform generation and their detection techniques, Section 3 reviews the background and related recent works, Section 4 explains the design of proposed photonic-based EW systems, Section 5 gives the details of experimental implementation of designed PEW system, Section 6 presents on-the-spot experimental validation results and analysis, and Section 7 gives the conclusion.

2. Principle of Radar Waveform Generation and Detection Techniques

The basic principles associated with the generation of radar signals/waveforms and their photonically detection techniques are briefed in this section. Time domain signal of the continuous wave (CW) radar can be generated as $S(t) = A[\cos(2\pi f_0 t) + \theta]$, where A is the signal amplitude, f_0 is the operating frequency, and θ is the initial phase of the radar signal. The linear frequency-modulated CW (LFMCW) signal can be generated as $S(t) = A.\sin\left(2\pi\left(f_0 \mp \frac{K}{2}t\right)t\right)$, where f0 is the starting frequency and K is the chirp rate, + sign indicates an up-chirp signal and the "−" sign is for a down-chirp signal. The LFM pulse signal is generated as

$$m(t) = \begin{cases} A.\sin\left(2\pi\left(f_0 - \frac{K}{2}(t - nT_{PT})\right)(t - nT_{PT})\right), & nT_{PR} \le t \le nT_{PT} + \tau \\ 0, & elsewhere \end{cases} \quad (1)$$

where n is an integer, τ is the pulse width, K is the chirp rate, and nT_{PT} is the pulse repetition time (PRT). The RF-pulse signal is generated as $S(t) = A.\text{sinc}(\pi\beta t).\cos(2\pi f_c t + \phi)$, where s(t) is the RF pulse waveform as a function of time t, A is the amplitude of the pulse, β is the pulse bandwidth, fc is the carrier frequency, and ϕ is the phase offset. The impulse function is generated as $\delta(t) = \begin{cases} 0, & for\ t \ne 0 \\ \infty, & for\ t = 0 \end{cases}$, where t represents the real time. Multiplying this impulse function with any RF signal gives the RF-contained impulse signal. All these radar-generated signals are transmitted which actually have to be extracted back by using the process of demodulation using the PEWS. In photonics, demodulation refers to the process of extracting information or signals from a modulated optical carrier wave. Various demodulation techniques are employed in photonics, depending on the modulation scheme used. In direct detection, the intensity of the optical signal is modulated, and the information is encoded in the amplitude of the signal. The simplest demodulation method for this involves detecting the changes in the intensity of the optical signal. Photodetector can be used to convert the optical signal into an electrical current, and the variations in this current represent the modulating RF signal. If the optical power is modulated, the instantaneous power can be represented as $P(t) = P_0 + A_m cos(2\pi f_m t) cos(2\pi f_c t)$, where P_0 is the average optical power, A_m is the modulation depth, f_m is the modulation frequency, and f_c is the optical carrier frequency. In the coherent detection, both the amplitude and phase information of the optical signal are used to demodulate the RF signal. It is often used in the advanced modulation formats like quadrature amplitude modulation. A local oscillator is mixed with the incoming optical signal, and the resulting beat signal is processed to extract both amplitude and phase information. Balanced detectors and digital signal processing are commonly used in coherent detection systems. If the phase of the optical signal is shifted due to modulation, the received signal can be represented as $E(t) = A\cos(2\pi f_c t + \phi(t))$, where A is the amplitude of the optical carrier, f_c is the optical carrier frequency, and $\phi(t)$ is the phase modulation. After any of this modulation/demodulation, the radar signal will have a few key PDW parameters such as amplitude, frequency, phase, bandwidth, PRT, and pulse repetition frequency (PRF). The PRF is the number of pulses transmitted per unit time which is a critical parameter in radar systems because it determines how often pulses are emitted. It affects the system's capacity to detect moving objects and prevent range ambiguity. The PRT is the time between the start of one pulse and the start of the following pulse. PRT is used to adjust the range resolution of a radar system. It helps to eliminate range ambiguities by ensuring that the echoes of one pulse are heard before transmitting the following pulse. The PRT is inversely proportional to the PRF and influences the radar system's duty cycle. The duty cycle is the fraction of time the radar is actively transmitting pulses. A longer PRT results in a lower duty cycle, which is important for system that need to manage power consumption or heat dissipation. Therefore, the PRT = pulse width (PW) + listening time (LT) and PRF = 1/PRT. In photonics, RF limiters are used to protect sensitive optical receivers and other photonic components from the damage of high-power RF signals. The dense wavelength division multiplexing is a key technology in photonics and optical communication systems, which enables the simultaneous transmission of multiple optical signals (channels) over a single optical fiber, each operating at a different wavelength. This allows for a significant increase in the overall RF-carrying capacity of the fiber infrastructure. The multiplexer and demultiplexer are the devices used to combine and separate multiple optical signals, respectively. Therefore, the captured RF signals have to be transported and processed in/by the photonic circuits before the extraction of critical parameters of PDW record.

3. Background and Related Works

Stark et al. highlighted the significant impact of photonic components and technologies on traditional RF and digital EW jammer system architectures in their paper "Photonics for Electronic Warfare" [1]. Ghelfie et al. offer photonics-based solutions that are suggested for use in the field of EW systems, more precisely exploring the application of a spectrum scanner that was presented in a recent study. The research highlights improvements in tuning speed in addition to performance metrics like bandwidth, linearity, and sensitivity that are comparable to cutting-edge electronic commercial systems. Future improvements are also discussed in the article, with integrability and tuning speed being identified as major areas in need of development [3]. In a comprehensive study by De et al., the development of photonics radar applications from optics to conventional microwave systems was surveyed. The study highlights the dynamic nature of photonics radar research, showcasing current accomplishments and outlining future improvements [4]. A technique was proposed by Zhou et al., which involved splitting an optical carrier into two parts, one of which is phase-modulated and the other of which is intensity-modulated, and both parts are modulated by an unknown microwave signal. The RF powers of the two components are compared after photodetection in order to produce a frequency-to-power mapping. The method is simple and has been experimentally validated over a 13.5 GHz frequency range with a measurement error of less than 0.3 GHz [5]. Michael E. Manka discusses the most recent advancements in the Australian defense industry's research and development of microwave photonics systems and their integration into EW receivers [8]. Akhter et al. suggested a research project that builds a 5.3 GHz CW photonic radar and an empirical wavelet transform-based method. Propeller systems and cone-shaped targets, which are representative LSS targets in open-field studies, exhibit 99% agreement with conventional measurements. The created photonics radar shows to be accurate in detecting and describing the various actions of LSS airborne targets [10]. LaMarche et al. presented an adaptive innovation for sub-array-level mono-pulse ratio estimation, specifically for numerous snapshots of phased array data, according to a research study. Additionally, beam pattern distortion in adaptive beam-forming is discussed in the study, with a focus on maintaining the sum and delta beam pattern forms for precise target localization [11]. According to a paper by Zou et al., photonic-assisted microwave measurements are a novel kind of measurement that gauges microwaves using light. Broader frequency coverage, greater instantaneous bandwidth, reduced frequency-dependent loss, and immunity to EMI are just a few of the benefits they offer over conventional electronic measurements. The writers of this paper give a thorough summary of the most recent developments in photonic microwave measurements. They talk about the technology's potential in the future, including how software-defined architectures and photonic integrated circuits (PICs) can be used to enhance measurement performance [14].

Garenaux et al. highlight the need for high-purity signal transmission in radar systems. Photonics technology is now mature enough to provide low-noise, interference-resistant, wide-bandwidth analog transmission even in harsh environments. This paper presents optimized optical links for radar and multifunctional systems. RF photonics is now ready for use in radar and EW systems. Future research will concentrate on enhancing integration and reducing expenses [15]. Oliveira et al.'s article provides a comprehensive overview of photonic research currently underway at the Instituto Tecnologico de Aeronautica, which was funded by the Brazilian air-force EW center. The research investigates the performance of an acousto-optic power spectrum analyzer and integrated optic lithium niobate modulators using versatile computer-aided design methods. It presents an all-optical RF oscillator as a viable option for a highly stable EW signal generator by fusing a fiber optic feedback loop with an integrated Mach-Zehnder modulator (MZM). The use of integrated optic modulators in a beam-forming network intended for phased array antennas is also examined in this paper [16]. According to Choe et al., military RF systems need to be adjusted in line with how warfare has changed. This presents RF photonics technology with both an opportunity and a challenge. The paper employs a top-down analysis to investigate how photonics can be integrated into RF systems, taking into account changes and aligning requirements with its capabilities [17]. By using wavelength scanning of RF sidebands through a phase-shifted fiber Bragg grating's central transmission peak, Winnall and Hunter presented an all-optical scanning receiver system for EW applications. The system uses a semiconductor diode laser with current modulation to achieve fast wavelength scanning using simple and lightweight fiber optics. Outstanding characteristics encompass a wide 20 GHz bandwidth, with a sensitivity of 73 dBm and a frequency resolution of 50 MHz. This emphasizes how useful the system is for EW applications [19].

In order to identify and extract Doppler profiles of low-slow-small (LSS) aerial objects with numerous simultaneous behaviors, Akhter et al. describe a C-band CW RF-photonic sensor that recovers micro-Doppler signatures from low-RCS targets such as drones and bionic birds. The experimental findings illustrate its capacity to distinguish distinct target postures, demonstrating its usefulness in studying and identifying various actions [20]. J. Scott Rodgers discusses RF photonics technologies as a cutting-edge approach for adaptable, wideband, multifunctional systems used in radar, communications, EW, and sensing [21]. The EW functions in airborne settings are demonstrated via photonic components and subsystems in the research by Davis et al. [20]. Improving situational awareness and modifying messages in cluttered EM settings are two increasingly difficult problems that can benefit from the special qualities of photonics [23]. Shen et al. [21] presented a non-scanning frequency measuring technique supported by photonics that uses a detuning optical frequency comb and double-sideband carrier-suppressed signals to beat one another. It provides a promising method for high-accuracy frequency measurement in spectrally crowded situations, with potential applications in a wide range of RF signal frequency measurements [24]. Also, an article by R. Robinson discusses about the potential use of photonics in EW systems and the challenges that can arise while integrating, in detail [29].

As a result of the literature research and to the best of our knowledge, the inclusion of RF photonics into EW systems/ applications has become significant/inevitable and a growing necessity in order to have a multiband high-sensitive, compact, and EMI-free EW system. The key scientific contributions discussed in this study are to address this immediate necessity to the greatest extent feasible by designing/developing a photonic-based EW system for extracting CW, pulsed, and frequency/ phase-modulated radar waveforms.

4. Design of Photonic EW Systems – CW, Pulsed, and FMCW Radar Waveform Photonic Extractors

The proposed PEWS can detect various types of radar signals which is the main mission of any EW system. The optisystem software environment is initially used for designing three different optoelectronics PEWS architectures, and the same environment is used for their simulation & data analysis. The layout schematic for the design/simulation of a CW photonic-based EW system is shown in Figure 2. The main optoelectronic components used in the design of CW photonic EW system are optical carrier, optoelectronic modulator, RF signal generator, optoelectronic converter, and spectrum analyzer. An optical carrier at 1550 nm is generated using a CW laser with a power of 40 mW and a line width of 0.05 MHz. For RF signal generation, a sinusoidal signal of 3 GHz with a 90-degree phase offset is employed. The system uses a dual-port MZM as the optoelectronic modulator and a PIN photodiode for optical-to-electrical conversion.

Both the laser and RF sources are split into two branches using optical and electrical power splitters, respectively. The upper arms of the optical and electrical splitters serve as inputs to the MZM for modulating the optical carrier, while the lower arms are reserved for reference signals for subsequent down-conversion stages. The MZM, acting as an intensity modulator, receives optical input from a CW laser source, RF input from the upper arm of the power splitter, and a DC bias set according to the V-π of the modulator.

Within the MZM, the RF signal modulates the optical carrier, producing a modulated optical output that is amplified using a

Figure 2
Design schematic of a frequency-modulated continuous wave (FMCW) – photonic-based electronic warfare (PEW) system

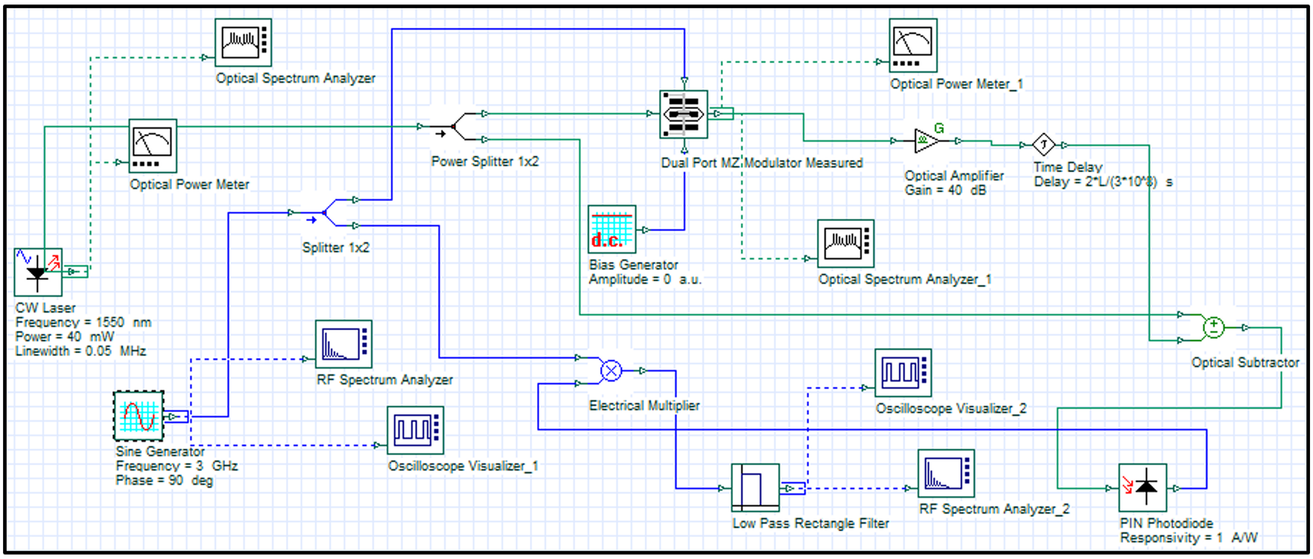


Figure 3
Photonics EW system extracted RF signatures: CW RF spectrum (a), pulsed RF spectrum (b), and FMCW RF spectrum (c)

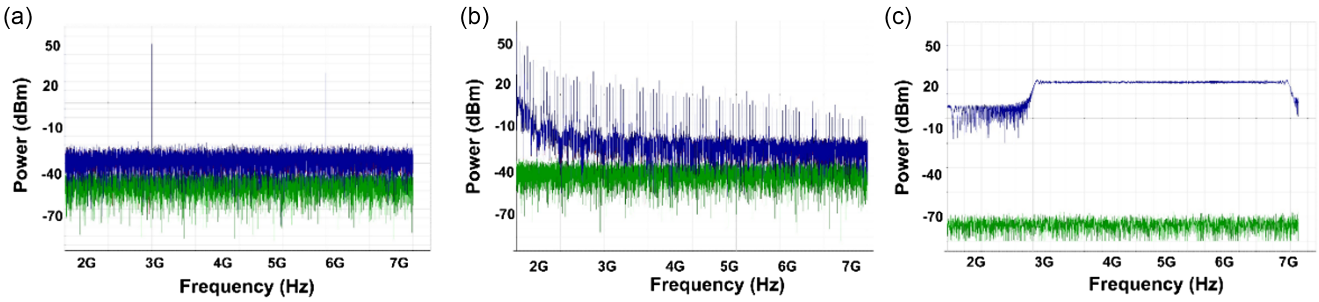


Figure 4
Design schematic of a pulsed photonic-based electronic warfare (PEW) system

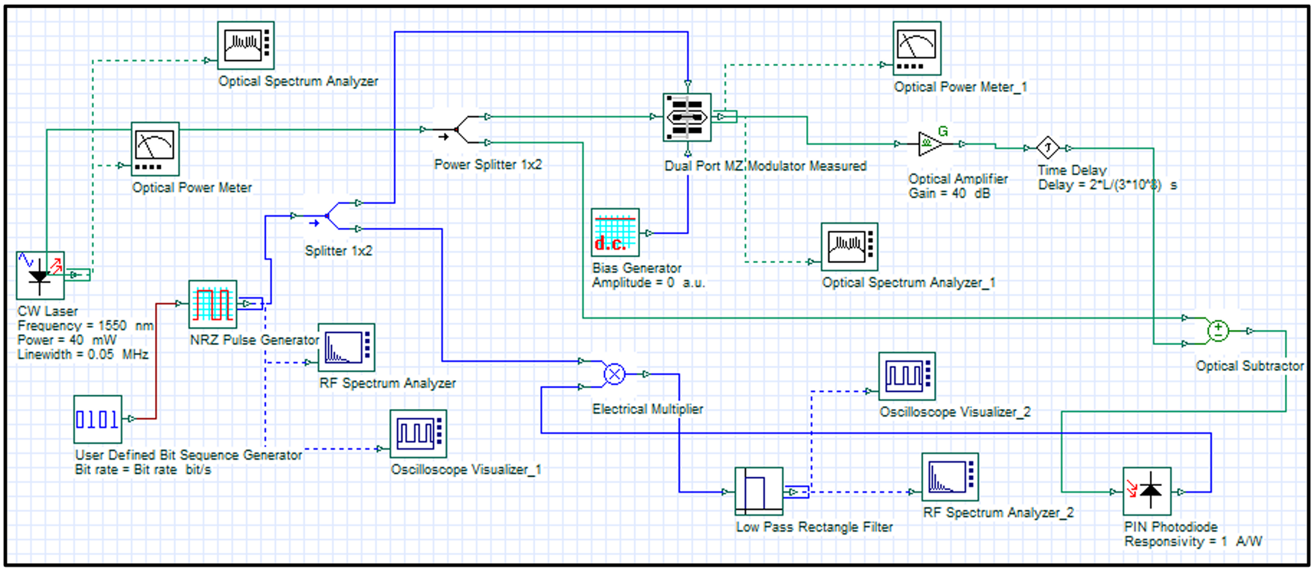
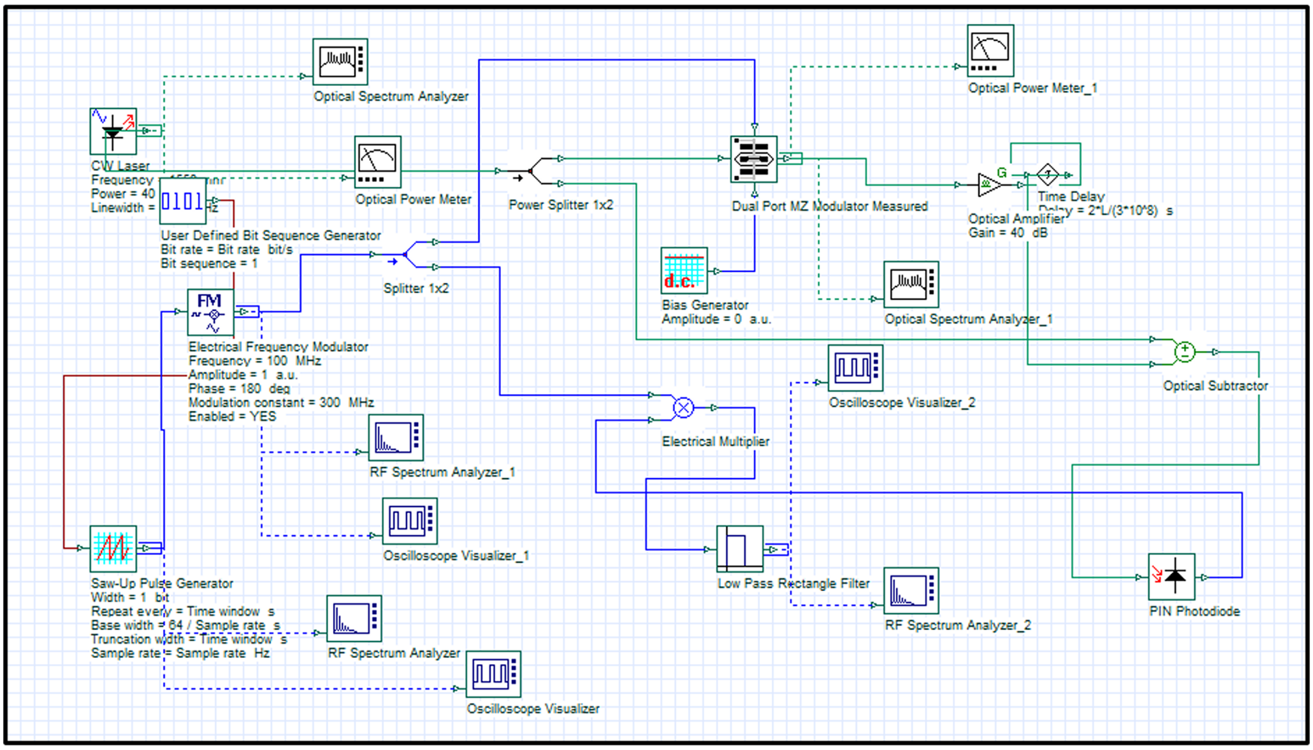


Figure 5
Design schematic of a frequency-modulated continuous wave (FMCW) – photonic-based electronic warfare (PEW) system

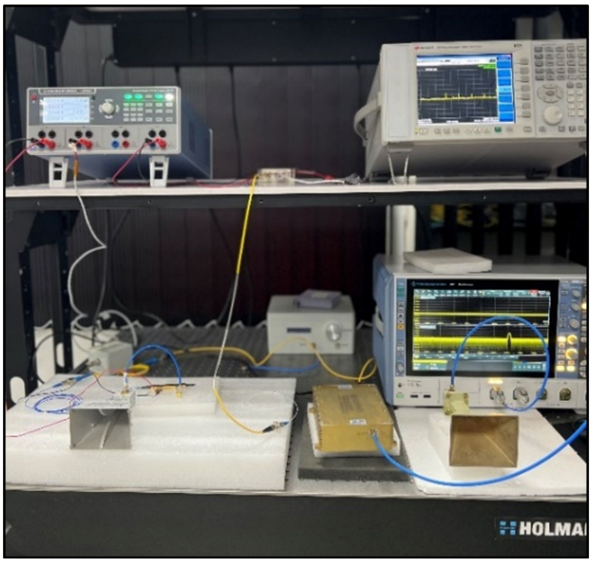


40 dB erbium-doped fiber amplifier. A time delay is introduced in the signal chain, and a reference signal is extracted from the lower arm of the optical power splitter for optical subtraction in the photonic down-conversion process. The optical-to-electrical conversion is performed using a PIN photodiode whose responsivity is 1 A/W.

The RF signal is mixed with a local oscillator obtained from the lower arm of the electrical splitter, and the resulting mixed signal passes through a low-pass filter to extract the instantaneous frequency. Finally, a real-time oscilloscope is employed as a visual component for observing the RF spectrum. This experimental setup enables the investigation and analysis of CW photonic EW systems providing insights into their functionality and performance characteristics.

The designed CW-PEWS is simulated in the optisystem environment, and the simulation results are shown in Figure 3(a). The radar-transmitted 3 GHz and 6 GHz CW RF signals are accurately measured which witnesses the detection accuracy of our CW signal extraction PEWS design. To design and simulate the pulsed photonic EW system and FMCW photonic EW system, modifications are made to the RF signal generation setup, as shown in Figures 4, and 5, respectively. For the pulsed photonic EW system, the CW RF signal generator is replaced with a pulse generator while for the FMCW photonic EW system, a sweep signal generator substitutes the CW RF signal generator. In the pulsed photonic EW setup, a non-return-to-zero bit sequence is utilized as input to generate pulses via a pulse generation circuit. The generated pulses serve as the RF signal for the pulsed photonic EW system. For the FMCW photonic EW system, a bit sequence is fed into a ramp generator circuit, generating a saw-tooth waveform with a width of 1 unit and a sample rate of 15E6 Hz. Subsequently, an electrical frequency modulator is employed to produce a LFMCW signal. This signal is then directed to the RF input of the MZM. This setup allows for the evaluation of the effectiveness and versatility of photonic techniques in EW applications. The extracted simulation results of pulsed and FMCW RF signal are shown in Figure 3(b), and (c), respectively. The results prove the accuracy of our proposed/designed PEWS in detection of the pulsed and FMCW RF signals.

Figure 6
A photograph of designed/implemented photonic-based EW system



5. Experimental Implementation of Designed Photonic EW Systems

Upon the successful design and simulation of photonic-based CW, pulsed, and FMCW signatures extracting EW systems, we proceeded into the experimental implementation of the same for the open-field EW applications. The designed PEWS consists of various hardware optoelectronics, and photonics components as shown in Figure 6. The key components used in our implementation of PEWS are wideband 12 dBi gain antenna, intensity modulatable high RF sensitive MZM, optical 1550 nm source, optical amplifier, large RF bandwidth, i.e., 60 GHz, optical detector, high-gain (i.e., 40 dB) electrical amplifier, 16 GHz real-time oscilloscope (RTO), 14 GHz RF signal analyzer, high-speed analog to digital converter, power supply unit, and single mode optical fiber cables. All these photonic components are connected using the 9-micron single-mode fiber cables/connectors, as shown in Figure 6. An in-house-developed radar system [18, 34] is used to generate all the radar signatures/ waveforms such as CW signal, pulsed signal, pulse-compressed signal, and frequency-modulated waveforms. The procedures followed in our research work to experimentally validate our PEWS are (i) switch the radar system to generate the different radar waveforms such as CW, plain pulse, RF-pulse, FMCW signal, impulse waveform, Barker code, Frank code, frequency-compressed pulse, etc., (ii) transmitting the generated radar waveform towards the designed PEW system, (iii) capturing the remotely transmitted radar waveforms by the developed PEW system, (iv) logging the samples of received radar signals (after down conversion) in the MATLAB environment in case of post-processing (please refer to Section 6), otherwise for the direct measurement, passing the captured signals into the RTO for temporal/spectral imaging, and signal analyzer for spectral/ time-frequency (T-F) imaging, and (v) post-processing the MATLAB logged samples and generating finally the PDW record.

The generated radar waveforms are transmitted toward the developed PEWS in order to immediate the radar transmission and RF signal capturing phenomenon of the EW system. A part of the generated radar signal (CW, RF-pulse, & FMCW) is shown in Figures 7, 8, 9, and 10 with their spectral profile and spectrogram,

Figure 7
Experimental results of designed PEWS with multicomponent CW RF signals (a–b)

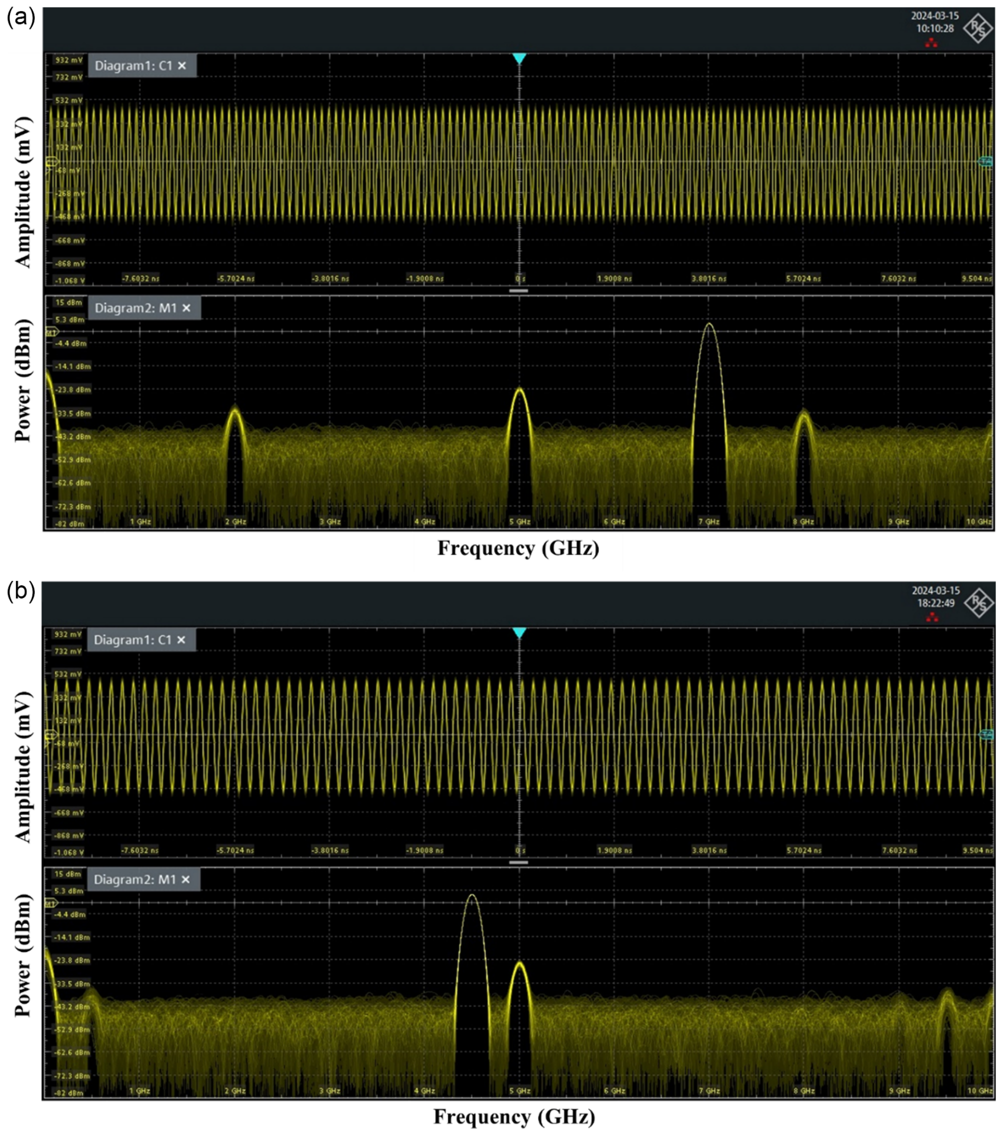
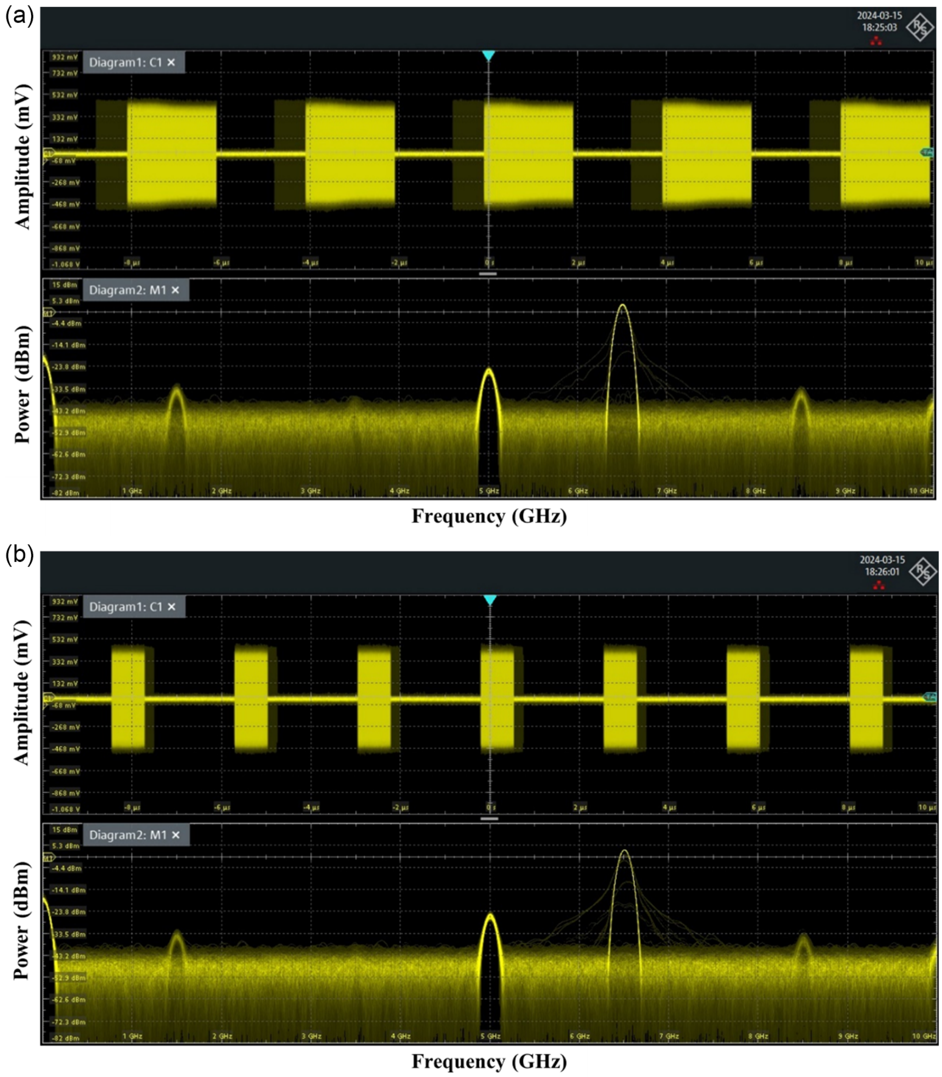


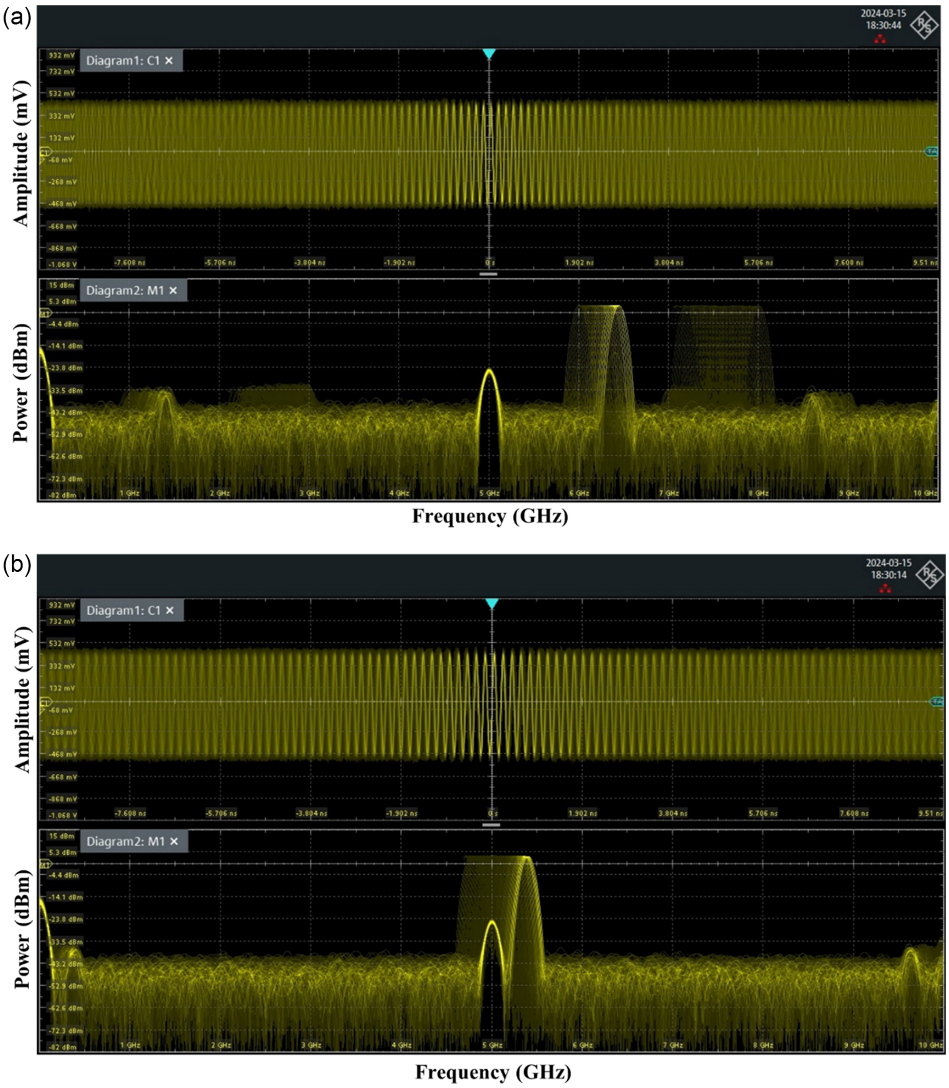
Figure 8
Experimental results of designed PEWS with multicomponent multiple-pulse-width RF signals (a–b)



i.e., T-F images. In the RF CW mode, the radar system transmitted a DC-biased multicomponent RF signal whose frequencies are 2 GHz, 5 GHz, 7 GHz, and 8 GHz. The results of our PEWS captured temporal and its spectral signatures are shown in Figure 7(a). As therein, the time domain representation of the captured RF signal has multicomponent which are clearly detectable in the generated spectral profile of the same CW signal.

The measurement parameters of the PEWS result for this CW signal are as follows: the amplitude is ± 31 mV, dominant frequency components are 2 GHz, 5 GHz, 7 GHz, & 8 GHz, and the peak power of the received signal −33.7 dBm. Similarly, another set of DC-biased RF CW waveform generated at the frequencies of 4.5 GHz, and 5 GHz at the peak power of +5.1 dBm, and Figure 7(b) shows their spectral profile accurately. In the RF-pulse mode, two different pulse (i.e., PRT of 4 µs, & 2.75 µs, and pulse width of 2 µs and 740 ns)-modulated RF signal are transmitted, as shown in Figure 8(a–b), toward the designed PEW system, and their respective spectral profile is also shown in Figure 8(a–b). As therein, the temporal and spectral profiles clearly illustrate the radar signatures and its key (pulse width, PRT, and carrier frequencies) parameters. In the modulation mode, two different LFMCW signals of bandwidth 2 GHz (i.e., 6–8 GHz) and 1 GHz (4.5–5.5 GHz), as shown in Figure 9(a–b), respectively, are transmitted. The measurement results of our PEW system are also shown in Figure 9(a–b) which clearly shows the FM sweep at 6–8 GHz and 4.5–5.5 GHz, respectively. The spectrogram, i.e., T-F image, corresponding to a 6.5 GHz CW radar signal is shown in Figure 10(a). All these experimental results prove that our designed photonic-based EW system is capable of accurately extracting the radar signatures and measuring their key parameter in the RF bands covering VHF through C-band. Further, in order to investigate the T-F imaging capability of our designed photonic-based EW system for a steeped FMCW signal, we have operated the radar system varying its frequency from 2 to 4 GHz in a step of 0.15 GHz, transmitted toward the PEW system and the instantaneous RF frequency and the stepped profile of RF frequency are shown in Figure 10(b), in which the T-F image precisely detects and shows the steeped profile of radar signature.

Figure 9
Experimental results of designed PEWS with multicomponent frequency-modulated CW signals (a–b)

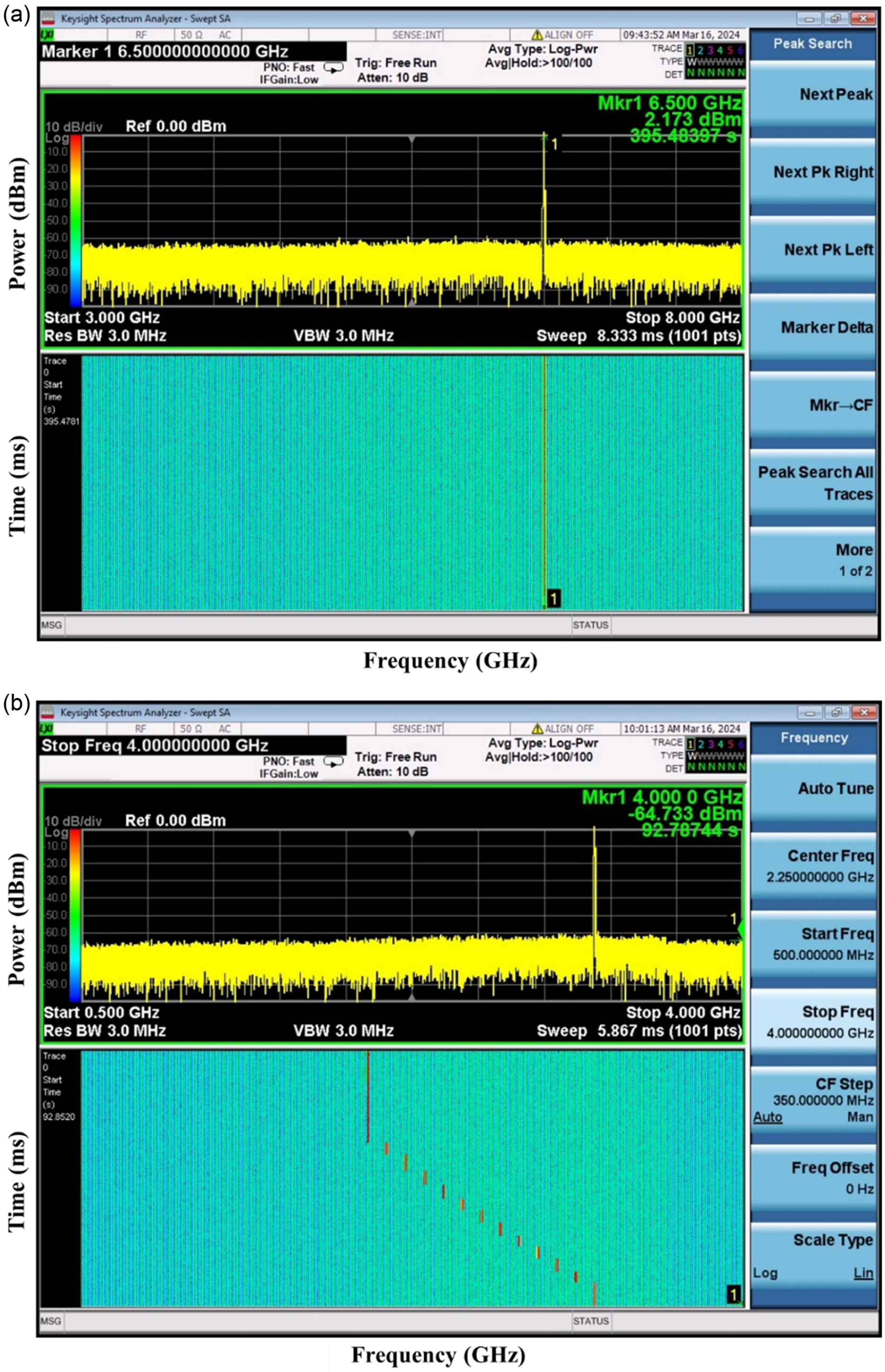


6. On-the-Spot Performance Validation of Photonic EW Systems

In order to experimentally validate the designed and implemented photonic-based EW system with all possible radar waveforms, open-field experiments are conducted transmitting different radar waveforms from a distant radar system and the developed PEWS is subjected for the collection of all the radar signature and MATLAB-based EW signal processing to extract the temporal, and spectral primary PDW parameters. A portion of those results collected on-the-spot open-field experiments are shown in Figure 11(a–h). In all these on-the-spot validation experiments, the waveforms of the radar system are tuned one to another, i.e., CW to plain pulse, plain pulse to RF-pulse, RF-pulse to frequency-modulated pulse, frequency-modulated pulse to phase-modulated pulse, & back, over the time, in order to mimic the dynamic waveform change profile/nature of the stealth radar system, finally, the acquired EW signals are logged and then transferred into the MATLAB environment. As a test case, a continuous sinusoidal wave is generated at the frequency of 50 Hz with the sampling frequency of 1 KHz, as shown in Figure 11(a), and the same is transmitted toward the PEWS. The PEWS receiver captures the 50 Hz CW signal for the period of every 1 s and subjects it to the spectral profile estimation as detailed in [34]. The result of the spectral estimator is shown in Figure 11(c) which clearly shows the spectral signature of the captured CW signal, i.e., the dominant frequency component present in the signal is 50 Hz. In the second test case, the radar model is switched to plain pulse transmission whose temporal signal is shown in Figure 11(b), therein, the pulse repetition frequency is 100 Hz, sampling frequency is 10 KHz, and pulse width/duty cycle is 20%.

The designed PEWS captured the plain pulse for every one-second period, computed the spectral signature, and the result of a 1 s temporal signal is shown in Figure 11(d), which proves the capability of our proposed PEWS for receiving the plain pulse. Figure 11(d) clearly shows the “sinc-function” spectral response [18] close to the DC for the plain pulse and a dominant frequency single-tone peak at 100 Hz for the plain pulse’s PRF, which are the actual EW signatures of the captured plain pulse signal. In the

Figure 10
Spectrum result of single-tone and stepped-frequency-modulated CW signals (a–b)



third test case, the radar model is switched to the sinusoidal pulse mode as shown in Figure 11(e) whose frequency is 500 Hz, sampling frequency is 10 KHz, pulse width/duty cycle is 50%, & PRF is 1 Hz, and the same is transmitted. The result of our PEWS for this sinusoidal pulse signal is shown in Figure 11(g); which accurately measures the EW frequency signature of the received signal at 500 KHz. Please note that in this experiment a low-pass filter of cut-off frequency 2 Hz is applied; hence, the magnitude around the DC is blocked in the result. This is the reason why does the PRF is nor shown in the result. In the fourth test case, the radar transmitter is switched into the LFMCW signal whose parameters are frequencies 30 Hz through 100 Hz, sampling frequency 10 KHz, and sweep PRT 10 s, as shown in Figure 11(f). The processed respective result of our PEWS for this LFMCW signal is shown in Figure 11(h) which clearly illustrates the instantaneous bandwidth of 80 Hz, i.e., Flow is 30 Hz, and Fhigh is 100 Hz. In order to validate the performance of our PEWS optoelectronic architecture for the inter-pulse-modulated radar

Figure 11
Performance validation of developed PEWS with the radar signatures of CW signal (a), plain pulse signal (b), RF-pulse signal (e), and linear frequency-modulated signal (f) with their respective spectral profile in (c), (d), (g), and (h), respectively

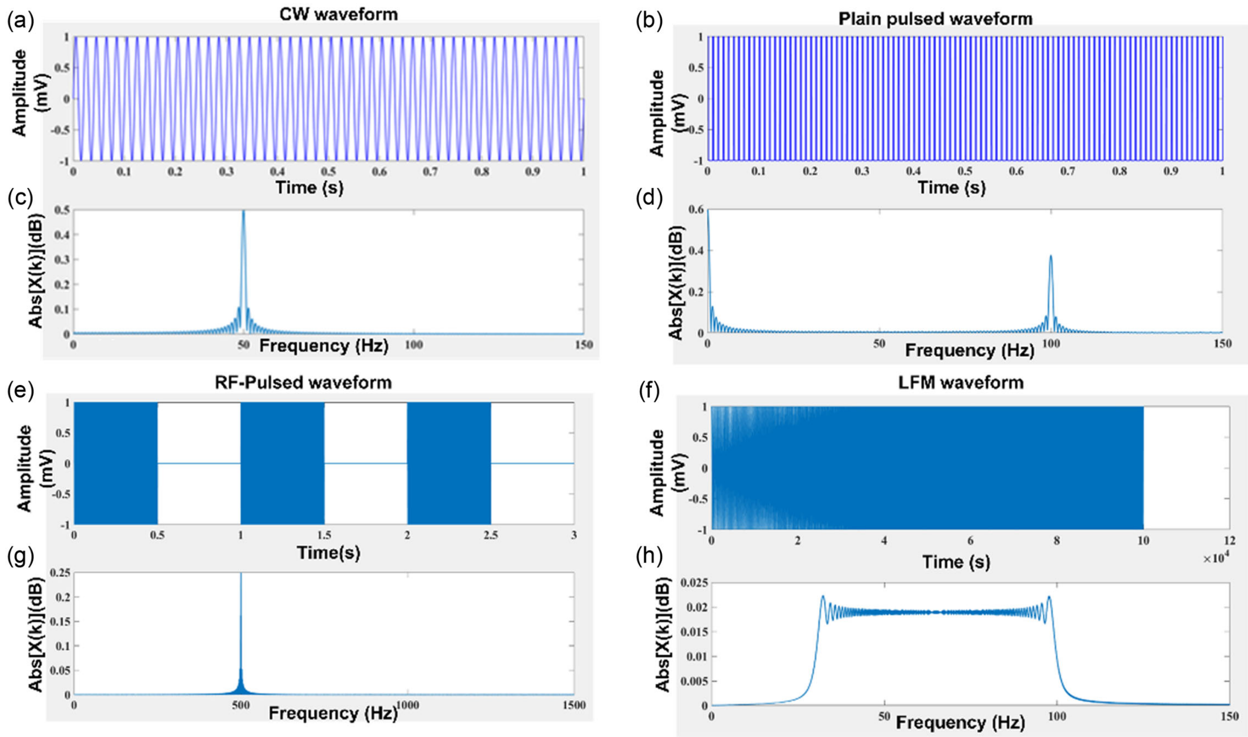
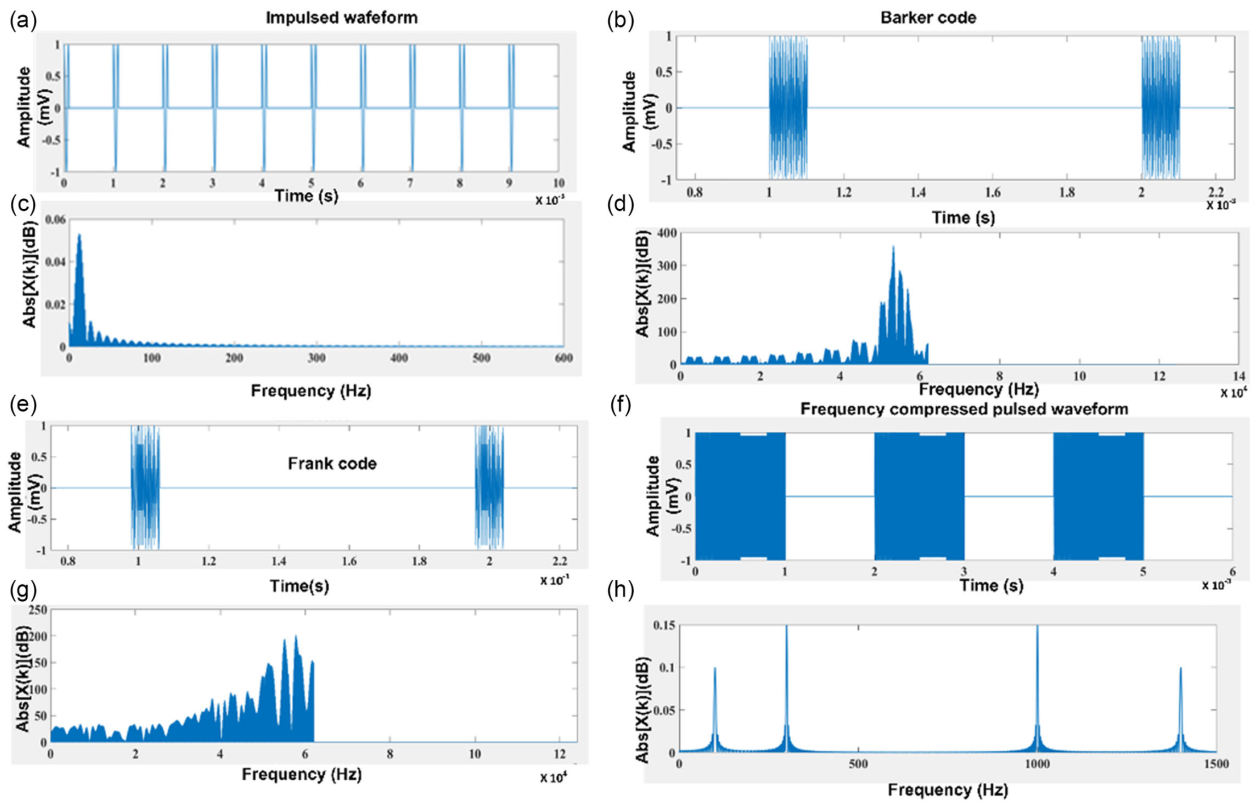


Figure 12
Performance validation of developed PEWS with the radar signatures of impulse signal (a), Barker code signal (b), Frank code signal (e), and frequency-compressed pulse signal (f) with their respective spectral profile in (c), (d), (g), and (h), respectively



waveforms, the radar system is operated in another four different modulation schemes as impulse signal, Barker code signal (binary phase modulation), Frank code signal (poly-phase modulation), and frequency-compressed pulse signal as shown in Figure 12(a), (b), (e), and (f), respectively. An impulse of 0.2E-3 pulse width and ≈1E-3 off period containing a cycle of 5 KHz frequency is generated as shown in Figure 12(a) and transmitted. The processed respective spectral profile is shown in Figure 12(c) which is a "sinc-function" and shows the frequency present in the on-period along with the pulse repetition frequency. In the second test trail, a barker code of B7 is generated by modulating the binary phase (i.e., 0o or 180o) of a sinusoidal signal as shown in Figure 12(b), and its PEWS processed spectral signal is shown in Figure 12(d) which clearly illustrates the fundamental frequencies present in the sinusoidal signal. The reason for the occurrence of different low-magnitude frequency components is the signal amplitude shift happening during the time-instant of phase shift within the pulse-on period.

In the third trial test, a Frank code is generated by the radar system modulating a sinusoidal signal at its four-phase values (i.e., 0o, 90o, 180o, or 270o) as shown in Figure 12(e) and transmitted toward the PEWS, and its processed results are also shown in Figure 12(g). As mentioned above, the spectrum is not a single tone due to the impulse nature of phase shift that happened during the multi-phase modulation of Frank code. In the last trial test, four different frequencies of continuous sine waves of 100 Hz, 300 Hz, 1000 Hz, and 1400 Hz at different time intervals of 0.2 s, 0.5 s, 0.8 s, and 1 s, respectively are generated, as shown in Figure 12(f) and transmitted. The result of our PEWS is shown in Figure 12(h) evidence the accurate reception of all those frequency components present in the received EW signal.

Therefore, as proved in the simulation, indoor, and on-the-spot experimental results, our developed photonic-based EW system is capable of capturing the radar signatures and processing them to illustrate/measure the spectral profile/key parameters that are pertaining to their remote sources.

7. Conclusion

The evolution of EW systems and PEW systems has been briefed right from the scenario of World War I. The significance of incorporation of photonics into the EW technology/applications is detailed. A comparative analysis of EW systems with the PEW systems, in terms of several key parameters, is performed and reported. A regressive state-of-the-art literature review/survey is performed in order to understand the worldwide research scenario and industrial developments happening in the field of PEW systems, and the outcome of the review is reported. Design principles of different radar waveforms, their RF-optical modulation techniques, and their effective demodulation techniques are presented with the essential background mathematical concepts. The design, modeling, and evaluation of a CW, pulsed, and FMCW photonic EW system are done in optisystem/MATLAB environments. The preformation of optisystem environment-designed CW, pulsed, and FMCW PEWS are verified using the RTO and spectral-profiling software tools. The designed PEWS is implemented using the optoelectronic and photonics components whose hardware design and its realization methodologies are detailed. The accuracy and efficiency of our proposed/implemented PEW system are examined by on-the-spot experiments transmitting, and processing the CW, plain pulse, RF-pulse, FMCW, impulse, Barker code, Frank code, and frequency-compressed pulse, and the results proved that our proposed/implemented design is appropriate for the intended missions. The RF CW signal frequencies, PRTs, pulse widths, phase modulations, poly-phase modulations, sweep frequencies, and RF power levels are varied, during the system performance investigations, as 100 Hz through 8 GHz, 10 ms through 2 μs, 750 ns through 2 ns, 0o, & 180o, 0o, 90o, 180o, & 270o, and −84 dBm through 30 dBm, respectively. Implementing the entire system in a compact/packaged from and subjecting it to the real-field operations is one of our ongoing researches. However, the designed PEWS is of high-cost and a complex one due to its configuration using the discrete optoelectronic components, which can be largely reduced by incorporating them in the form of PICs. Also, increasing the instantaneous operation RF bandwidth and performing most of the RF/EW signal processing in the photonics domain itself improve the effectiveness of PEW system which are our near-future research works.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data are available from the corresponding author upon reasonable request.

Author Contribution Statement

Devesh Khanna: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing – original draft. **Sampurna De:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Visualization. **A. A. Bazil Raj:** Formal analysis, Resources, Data curation, Writing – original draft, Writing – review & editing, Supervision. **Bharat S. Chaudhari:** Formal analysis, Resources, Data curation, Writing – review & editing, Project administration.

References

[1] Stark, A. J., Davis, K., Ward, C., & Gray, J. (2014). Photonics for electronic warfare. In *2014 IEEE Avionics, Fiber-Optics and Photonics Technology Conference*, 3–4. https://doi.org/10.1109/avfop.2014.6999438

[2] Ghelfi, P., Scotti, F., Onori, D., & Bogoni, A. (2019). Photonics for ultra-wideband RF spectral analysis in electronic warfare applications. *IEEE Journal of Selected Topics in Quantum Electronics*, *25*(4), 1–9. https://doi.org/10.1109/jstqe.2019.2902917

[3] De, S., & Bazil Raj, A. A. (2023). A survey on photonics technologies for radar applications. *Journal of Optics*, *52*(1), 90–119.

[4] Zhou, J., Fu, S., Aditya, S., Shum, P. P., & Lin, C. (2009). Instantaneous microwave frequency measurement using photonic technique. *IEEE Photonics Technology Letters*, *21*(15), 1069–1071. https://doi.org/10.1109/lpt.2009.2022637

[5] Sun, H., Shimada, M., & Xu, F. (2017). Recent advances in synthetic aperture radar remote sensing—systems, data processing, and applications. *IEEE Geoscience and Remote Sensing Letters*, *14*(11), 2013–2016.

[6] Manka, M. E. (2008). Microwave photonics for electronic warfare applications. In *2008 International Topical Meeting on Microwave Photonics Jointly Held with the 2008 Asia-Pacific Microwave Photonics Conference*, 275–278.
[7] Ritchie, M., Fioranelli, F., Borrion, H., & Griffiths, H. (2017). Multistatic micro-Doppler radar feature extraction for classification of unloaded/loaded micro-drones. *IET Radar, Sonar & Navigation*, *11*(1), 116–124.
[8] Akhter, N., Raj, A. A. B., & Prabu, K. (2023). Photonics radar based LSS targets' postures' mD and cadence frequency imaging using empirical wavelet transform technique. *The Imaging Science Journal*, *6*, 1–17.
[9] Iqbal, K., Zhang, M., Piao, S., & Ge, H. (2020). Evolution of sonobuoy through history & its applications: A survey. In *2020 17th International Bhurban Conference on Applied Sciences and Technology*, 543–554.
[10] Alfred, P. (2017). *Instruments of darkness: The history of electronic warfare, 1939–1945*. UK: Pen and Sword.
[11] Sass, R., & Schmidt, A. G. (2010). *Embedded systems design with platform FPGAs: Principles and practices*. USA: Morgan Kaufmann.
[12] Zou, X., Lu, B., Pan, W., Yan, L., Stöhr, A., & Yao, J. (2016). Photonics for microwave measurements. *Laser & Photonics Reviews*, *10*(5), 711–734. https://doi.org/10.1002/lpor.201600019
[13] Garenaux, K., Merlet, T., Alouini, M., Lopez, J., Vodjdani, N., Boula-Picard, R., . . . , & Chazelas, J. (2007). Recent breakthroughs in RF photonics for radar systems. *IEEE Aerospace and Electronic Systems Magazine*, *22*(2), 3–8. https://doi.org/10.1109/maes.2007.323292
[14] Oliveira, J. E. B., Alves, F. D. P., & Mattei, A. L. P. (1999). Trends in photonics applied to electronic warfare at Brazilian airforce. In *1999 SBMO/IEEE MTT-S International Microwave and Optoelectronics Conference, 2*, 599–602. https://doi.org/10.1109/imoc.1999.866252
[15] Choe, J. Y. (2005). Defense RF systems: Future needs, requirements, and opportunities for photonics. In *2005 International Topical Meeting on Microwave Photonics*, 307–310. https://doi.org/10.1109/mwp.2005.203600
[16] Rahman, A., Lubecke, V., Yavari, E., Gao, X., & Boric-Lubecke, O. (2017). High dynamic range DC coupled CW Doppler radar for accurate respiration characterization and identification. In *2017 89th ARFTG Microwave Measurement Conference,* 1–4.
[17] Winnall, S. T., & Hunter, D. B. (2002). A fibre Bragg grating based scanning receiver for electronic warfare applications. In *2001 International Topical Meeting on Microwave Photonics. Technical Digest*, 211–214. https://doi.org/10.1109/mwp.981833
[18] Li, J., Zhang, F., Xiang, Y., & Pan, S. (2021). Towards small target recognition with photonics-based high resolution radar range profiles. *Optics Express*, *29*(20), 31574–31581.
[19] Rodgers, J. S. (2013). Technologies for RF photonics in wideband multifunction systems. In *2013 IEEE Avionics, Fiber-Optics and Photonics Technology Conference*, 7–8. https://doi.org/10.1109/avfop.2013.6661596
[20] Davis, K., Gray, J., & Stark, A. (2013). Photonic components and subsystems for electronic warfare. In *2013 IEEE Avionics, Fiber-Optics and Photonics Technology Conference*, 47–48. https://doi.org/10.1109/avfop.2013.6661616
[21] Shen, Z., Jin, C., He, Q., Zhang, Z., & Zhao, Y. (2019). Photonics-assisted non-scanning high-accuracy frequency measurement using low-speed components. *IEEE Photonics Journal*, *11*(4), 1–8. https://doi.org/10.1109/jphot.2019.2922546
[22] Devgan, P. S., Brown, D. P., & Nelson, R. L. (2015). RF performance of single sideband modulation versus dual sideband modulation in a photonic link. *Journal of Lightwave Technology*, *33*(9), 1888–1895.
[23] De, S., & Raj, A. B. (2021). Photonics radar modeling and simulation in opti-system platform for high resolution target detection. In *2021 International Conference on Smart Generation Computing, Communication and Networking (SMART GENCON)*, 1–7.
[24] Xue, Z., Li, S., Xue, X., Zheng, X., & Zhou, B. (2021). Photonics-assisted joint radar and communication system based on an optoelectronic oscillator. *Optics Express*, *29*(14), 22442–22454.
[25] Adamy, D. (2001), *EW 101: A first course in electronic warfare*. USA: Artech House.
[26] Zhang, W., Tait, A., Huang, C., Ferreira de Lima, T., Bilodeau, S., Blow, E. C., . . . , & Prucnal, P. (2023). Broadband physical layer cognitive radio with an integrated photonic processor for blind source separation. *Nature Communications*, *14*(1), 1107. https://doi.org/10.1038/s41467-023-36814-4
[27] Bres, C. S., Zlatanovic, S., Wiberg, A. O., Adleman, J. R., Huynh, C. K., Jacobs, E. W., . . . , & Radic, S. (2011). Parametric photonic channelized RF receiver. *IEEE Photonics Technology Letters*, *23*(6), 344–346. https://doi.org/10.1109/lpt.2011.2105470
[28] Zhang, P., Tan, Z., Ding, Z., & Guo, L. (2021). Simulation analysis of balance detection technique in coherent optical receiver. *Optics and Photonics Journal*, *11*(8), 301–313. https://doi.org/10.4236/opj.2021.118020
[29] Callahan, P. T., Dennis, M. L., & Clark Jr, T. R. (2012). Photonic analog-to-digital conversion. *Johns Hopkins APL Technical Digest*, *30*(4), 280–286.
[30] Alhaji Musa, S., Raja Abdullah, R. S. A., Sali, A., Ismail, A., & Abdul Rashid, N. E. (2019). Low-slow-small (LSS) target detection based on micro Doppler analysis in forward scattering radar geometry. *Sensors*, *19*(15), 3332.
[31] Mahjoubfar, A., Churkin, D. V., Barland, S., Broderick, N., Turitsyn, S. K., & Jalali, B. (2017). Time stretch and its applications. *Nature Photonics*, *11*(6), 341–351. https://doi.org/10.1038/nphoton.2017.76
[32] Huang, H., Zhang, C., Zheng, W., Chen, Y., Yang, H., Yi, Z., . . . , & Qiu, K. (2020). Photonics-assisted multi-band microwave receiver based on spectrum analysis and coherent channelization. *Frontiers in Physics*, *8*, 562456. https://doi.org/10.3389/fphy.2020.562456
[33] Ghelfi, P., Onori, D., Laghezza, F., Scotti, F., Bogoni, A., Albertoni, A., & Tafuto, A. (2015). An RF scanning receiver based on photonics for electronic warfare applications. In *2015 European Radar Conference (EuRAD)*, 197–200.
[34] Laurenzis, M., Hengy, S., Hommes, A., Kloeppel, F., Shoykhetbrod, A., Geibig, T., . . . , & Christnacher, F. (2017). Multi-sensor field trials for detection and tracking of multiple small unmanned aerial vehicles flying at low altitude. In *Signal Processing, Sensor/Information Fusion, and Target Recognition XXVI*, *10200*, 384–396.
[35] Chen, B., Fan, Y., Tian, Z., Wang, W., Kang, B., Jiang, W., & Gao, Y. (2019). An ultra-wideband microwave photonic channelized receiver with zero-IF architecture. *Applied Sciences*, *10*(1), 30. https://doi.org/10.3390/app10010030
[36] Zhang, Z., Li, H., Zhang, S., & Liu, Y. (2014). Analog-to-digital converters using photonic technology. *Chinese Science Bulletin*, *59*(22), 2666–2671. https://doi.org/10.1007/s11434-014-0403-6
[37] Liu, Y., Zhang, Z., Burla, M., & Eggleton, B. J. (2022). 11-GHz-bandwidth photonic radar using MHz electronics. *Laser & Photonics Reviews*, *16*(4), 2100549.

[38] Kim, Y. H., Song, K. H., Han, J. W., & Kim, H. N. (2014). Radar scan pattern analysis for reduction of false identification in electronic warfare support systems. *IET Radar, Sonar & Navigation*, *8*(7), 719–728.

[39] Zhang, Z., Liu, Y., & Eggleton, B. J. (2021). Photonic generation of radar signals with 30 GHz bandwidth and ultra-high time-frequency linearity. *arXiv Preprint*: *2111.15458*.

[40] Al-Khawaja, A., & Sadkhan, S. B. (2021). Intelligence and electronic warfare: Challenges and future trends. In *2021 7th International Conference on Contemporary Information Technology and Mathematics*, 118–123.

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