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Innovations and Applications of High-Power Microwave Impulse Radiating Antenna: A Review

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ABSTRACT

The increasing deployment of unmanned aerial vehicles (UAVs) across various domains has raised concerns regarding security and electromagnetic interference (EMI) threats. This study explores the intersection of high-power microwave (HPM) technologies, impulse radiating antennas (IRA), and electromagnetic pulse (EMP) systems for UAV detection, disruption, and neutralization. A comprehensive classification of intentional electromagnetic environments (IEME) is presented, outlining the potential vulnerabilities of UAV sensor modules to electromagnetic attacks. Various high-power antenna configurations, including slotted waveguide arrays, helical reflectarray, and circularly polarized reflectarray, are analyzed for their applicability in counter-UAV operations. Additionally, the role of dynamic geofencing and model predictive control in UAV flight restriction is examined to complement electromagnetic-based neutralization strategies. Experimental studies and simulation results demonstrate the feasibility of integrating HPM technologies with advanced antenna systems to achieve effective UAV mitigation. This research contributes to the advancement of directed energy applications for drone defense, offering insights into future security frameworks for agriculture.

Keywords: High Power Microwave (HPM), Impulse Radiating Antenna (IRA), Unmanned Aerial Vehicle (UAV)

INTRODUCTION

High Power Microwave (HPM) systems are advanced electromagnetic technologies that generate and emit intense microwave pulses in the frequency range of 200 MHz–5 GHz which can upset or damage an electronic system. This induced effect in an electronic system is commonly referred to as intentional electromagnetic interference (IEMI) [1].In addition to these continuous spectra, there are various narrow band signals that are often referred to as high-power microwave (HPM) environments [1]. HPEM systems are classified as follows:

1. Anti-electronics: made to damage or interfere with electronics, weapons, or hardware in order to prevent an adversary's systems from operating.

2. Anti-personnel: intended to hinder human functioning without inflicting significant harm to the body [1].

The compatible antenna is used for effective radiation towards the target as the type of antenna determines the directionality and efficiency of transmission. HPM technology enables the generation and radiation of high-energy electromagnetic pulses, which can be used for a variety of purposes, including electronic warfare, non-lethal deterrence, and secure communications.

Different categories of High Power Microwave Antenna for directive beam and their limitations i.e. a list of possible radiators [7].

1. Dipole Antenna- Not suitable for generating directive HPM beam
2. Log-Periodic Antenna- faced with the problem of driving the input port of the antenna with a high-power pulse.

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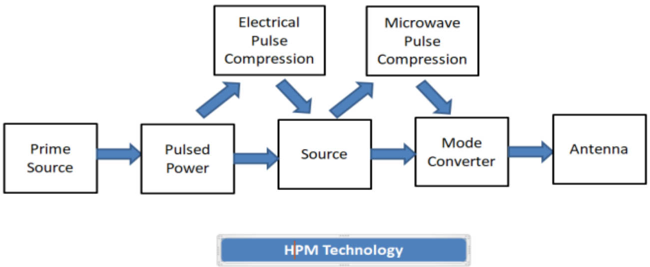
3. Leaky Pipe or an Array of Slotted Waveguides- will require a hundred of slots for GW of power used in HPM
4. Horn Array- It takes many horns to produce a large aperture plane in terms of wavelength dimensions
5. Dielectric Lens Antenna- An array of dielectric lenses fed by each horn is impractical approach to achieve large aperture
6. Reflector Antennas-size is too big.
7. Impulse Radiating Antenna- ability to deliver ultra-wideband, high-intensity electromagnetic pulses with high directivity and efficiency.



Impulse Radiating Antenna (IRA) Impulse Radiating Antenna (IRA) is a type of antenna that emits high-amplitude, short-duration electromagnetic pulses; IRA is one type of transient radar that is designed to meet the requirement for a radiating component. This type of radar aims to address a number of issues, including target discrimination in a highly crowded environment and target identification using aircraft scattering such as when looking over the ocean, and foliage penetration[8]. When comparing antennas of similar size (larger dimension),in terms of performance, IRA has a significant edge. The IRA nevertheless offers distinct advantages at the high end when compared other antennas with similar aperture areas because it is not affected by the TEM horn's high-frequency roll off issue. Finally, the IRA has some desirable directionality at low frequencies [8]. It has been found that an IRA can be built in at least three general ways. The fundamental concept is to create a rapidly increasing pulse on an antenna aperture in the shape of a plane wave. This can be accomplished using an array of several elements at or close to the antenna aperture (an array IRA), a paraboloid reflector powered by a TEM feed and usually having four arms (a reflector IRA), or a lens at the end of a TEM horn (a lens IRA) [9]. The development of HPM IRAs has progressed through several key phases parabolic reflectors combined with transverse electromagnetic (TEM) feed structures. These designs significantly improved directivity and radiation efficiency, enabling the generation of well-formed, high-power electromagnetic pulses

Table I Evolution of Impulse Radiating Antenna (IRA)

Year	Type	Key Features	Examples	Applications
1970-1980	Wideband IRA	Resistive loaded	Biconical Conical	Radar
1980-1990	Reflector IRA	Enhanced radiation efficiency	Parabolic reflector	Electromagnetic Warfare
1990-2000	TEM Horn IRA	Wideband impedance matching	TEM Horn IRA	High power Electromagnetic (HPEM)
2000-2010	Lens IRA	Improved Pulse Shaping	Dielectric lens	Mobile and airborne
2010-Present	UWB and Planar IRA	Improved phase center stability	Planar IRA	Agriculture security and geofencing
Present Future	HPM IRA	Neutralizing electronic threats	HPM IRA	Directed energy

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Research Article

Table II Types of High Power Microwave Antenna and their Parameter

Ref. Year	Antenna Type	Electric Field	Aperture Efficiency	Gain	Power handling Capacity
[2] 2019	Slotted waveguide	2.67 MV/m	-----	32.06 dBi	99.3%
[3] 2021	Helical Reflectarray	2.898KV/m	50.6 %	23.7 dB	358MW
[4] 2019	Array	3.597KV/m	90.43%	26.3 dB	96.5 MW
[5] 2022	Reflectarray	966V/m	58.76%	33.05 dBi	5 GW/m2
[11] 2022	Radial Line Slot	1.810KV/m	62.70%	32.0 dBi	>500MW

APPLICATIONS AND TECHNOLOGIES OF HIGH POWER MICROWAVE IMPULSE RADIATING ANTENNA (HPMIRA)

High-voltage pulses in the nanosecond range have been shown to penetrate into living cells to permeabilize intracellular organelles, and release Ca2+ from various internal stores. They provide a new approach to targeting intracellular organelles for many applications including activation of platelets and release of growth factors for accelerated wound healing and precise control of programmed cell death (apoptosis) which has been shown to cause complete elimination of melanoma tumors.[12] Both imaging and medical application require focusing the radiation to a minimum spot size. In imaging, a small spot size allows for a 3-D scan with a good spatial resolution. For therapy, a small spot size means that only the area at the focal point will be treated as opposed to the surrounding area with lower electric field (or power density)[10]The HPM technology has two configurations: continuous wave and pulsed wave. In opposition operations against drones, a continuous wave emits a steady stream of microwave energy over a large region. A pulsed wave produces high-power, short-duration microwave pulses that can be used to create precision drones. Pulsed-wave weapons are designed to disrupt or degrade the electrical components of an electromagnetic pulse (EMP) target group.[13]. Thus, High-Power Microwave Impulse Radiating Antennas (HPM IRA) have seen extensive advancements in recent years, leading to a variety of applications in defense, security, medical imaging and agriculture. Their ability to generate high-intensity electromagnetic pulses makes them suitable for applications requiring long-range detection, electronic warfare, and geo fencing.Their adaptability in scientific and technical breakthroughs is demonstrated by the wide range of applications these antennas serve, from tracking and target identification to medical imaging, telemetry, melanoma therapy, and drone neutralization. UAVs were originally invented for usage in military applications. Gradually UAVs were successfully employed in several civil applications like agriculture, policing, surveillance, recreational purposes, etc [24].

Table III Uses of Impulse Radiating Antenna (IRA) in various fields

Ref.	Antenna	Technique	Results	Application
1 [17]	Prolate Spheroidal Reflector (IRA)	dielectric lens to reduce the focal spot size,	The signal changes with or without the target.	Tracking and Target Detection
2 [23]	Prolate Spheroidal Reflector (IRA)	Sub-centimeter spatial resolution medical imaging	Electric Field strength is high	Imaging in Medicine
3 [19]	Antipodal Vivaldi (IRA)	proximity of the pipe and antenna for signal deterioration..	Planar fidelity factor is 0.81, whereas in the conformal free-space is 0.87	Telemetry

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Research Article

4 [20]	Prolate Spheroidal Reflector	Two antennas with PSR but fed with focus pulsed field at the second focal point	EM fields have been developed as minimally invasive treatments of tumors	Melanoma treatment
5 [18]	Helical Antenna	EMP effect for several distances	Accepted power close to stimulated power	Neutralize other drones

AGRICULTURAL APPLICATIONS

HPM has potential use in agriculture where the microwave pulses help to disrupt pests biological functions, neutralizing them without chemicals, eliminate fungal spores, bacteria, and viruses on plant surfaces and soil, which may pass through soil and vegetation allowing for the identification of subsurface anomalies, soil moisture analysis, and sophisticated crop health monitoring.

Unmanned aerial Vehicle (UAV): The rapid growth of modern agriculture can be attributed to machinery, irrigation, chemical inputs (such as fertilizers, insecticides, and herbicides), and other modern agricultural techniques. Agricultural security is the defense and adaptability of agricultural systems against risks that could impair supply networks, food production, and rural lifestyles. It includes steps to protect soil, water resources, livestock, crops, and agricultural infrastructure from threats that are biological, technological, economic, and natural. With the recent advances in technology, developing nations are plunging into securing their agricultural land with more efficient technology and drone technology is the new growth [1]. The main advantages of using UAVs for smart agricultural applications include mobility of UAVs in variable weather conditions, ability to capture high-resolution pictures from different ranges (average range 50 to 100 meters)[25] Therefore, UAVs are increasingly becoming an essential part of our everyday existence and have penetrated many areas of our industry. Since drones can be used for a variety of tasks, including disaster management, traffic control, weather analysis, search and rescue, monitoring, surveillance and freight delivery.[15[16]. Farms are vulnerable to vandalism which can damage crops, buildings, and equipment. The intentional or accidental introduction of pests, diseases, or invasive species can devastate crops and livestock, impacting food production and potentially causing widespread economic damage. Unmanned aerial vehicles (UAV's) or drones are aero planes that drive themselves without a pilot. They can fly on their own with pre-programmed flight paths, or they can be remotely controlled by a pilot on the ground. UAVs scope in various sectors, particularly in the field of precision agriculture, cinematography, and geospatial mapping, is examined for its transformative potential [6]. The expanding use of commercial drones has given rise to security concerns, introducing potential threats like jamming, spoofing, and denial of service attacks.[6]. Research on anti-drone techniques, such as their detection, identification, and neutralization, has grown in tandem with the rise in drone-related crimes. Effective neutralization techniques are crucial among these strategies to guarantee dependable defense against real threats. Although direct physical attacks, like nets or gunfire, are easy and obvious ways to capture or destroy drones, they are avoided due to the target's high speed and potential for secondary harm. To get over these restrictions, neutralizing techniques utilizing electromagnetic interference have recently been thoroughly researched. The majority of the initial research was restricted to examining how drones reacted to strong electromagnetic waves. Nonetheless, research on electromagnetic waves with different frequencies and waveforms has been carried very recently. [22]

Geo fencing: Geo-fencing refers to the use of technology to food production and potentially causing widespread economic damage. Unmanned aerial vehicles (UAV's) or drones are aero planes that drive themselves without a pilot and even carry out certain tasks autonomously. They create a virtual perimeter around a given region. The system responds by issuing an alert or the outdoor geo fencing is commonly based on Global Positioning System (GPS) technology that spatially outlines the no-flight zones for UAVs. The zones that are forbidden for flight can be constant (static) and dynamic [15].Geo fence is a common security mechanism used to keep UAVs out of restricted airspace, such as airports, military installations, and power plants. Usually, geo fence is used to compare the current location of the UAV with pre-defined or dynamically determined no-fly zones (NFZs) and other restricted areas. Any possible or current violations are then reported to the UAV operator. On certain UAV platforms, this could be followed by the drone's rotors stopping or an emergency landing being automatically initiated. Geofence

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Research Article

also used to avoid dangerous UAV-to-UAV collisions, particularly in urban airspaces [14]. The definition of a geo fencing policy is to bound the operating area of the drones is one of the main requirements a UAV has to satisfy to be certificated to fly [16]. Till now UAVs have been mostly used in warfare but in recent times due to their more economic cost, they have recently been employed for various tasks in agriculture. These drones for agricultural uses are equipped with different sensors a technology that allow them to collect data, monitor crops. On the other hand, there is a requirement that a UAV must have the ability to avoid a no-fly zone while deployed for a mission to increase safety and reliability [23]. The anticipated widespread use of unmanned aerial vehicles (UAVs) raises serious safety and security issues. These issues include disrupting busy airspaces, crashing into other UAVs, and trespassing in prohibited areas. One line of defense to lessen these risks has been proposed through geofencing which keep UAVs from flying into restricted areas and around other UAVs' perimeters. Also, impulse radiating antenna can be utilized in disrupting other drones, going certain boundaries of the farmland turning on or off.

Table III High Power Microwave parameters with Application

Parameter	**High Power Radar**	**Warfare(EW) and DEW**	**Biomedical and Imaging**	**Communication (UWB Systems)**
Frequency	0.3- 10 GHz	1- 20GHz	1 – 6 GHz	0.5 – 5 GHz
Peak Power	100MW-1GW	10 MW – 500 MW	<10 kW	<1KW
Pulse Width	0.1-10ns	0.1 – 5 ns	0.1 – 1 ns	0.5 – 5 ns
Repetition rate	10-1000Hz	1 – 100 Hz	1 – 10 kHz	100 – 1000 kHz
Antenna Type	Parabolic Reflector Array	Lens-fed IRA	Compact Conical IRA	Planar Vivaldi Array
Gain	25-40dBi	20 – 35 dBi	10 – 25 dBi	5 – 20 dBi
Beam width	3-10°	5- 20°	20 – 60°	30 – 90°
Directivity	High	High	Medium	Low
Polarization	Linear/Circular	Linear	Linear	Linear
Antenna Aperture	1 – 3 m	0.5 – 2 m	0.2 – 0.5 m	0.1 – 0.5 m
Target distance	00-1000 km	1 – 100 km	0.1 – 10 m	0.5 – 50 m

HPM EFFECT ON UAV FROM DISRUPTION TO DESTRUCTION

Impact of pulses on various electronic components:

An investigation of high-power microwaves (HPMs) impact on AVs was conducted. HPM generator based on an impulse compressor was used in research. Compression allowed for producing impulses with fields intensity exceeding 50 kV/m and power ~3 MW. Conducted tests included analyzing the response of UAV when subjected to intense HPM radiation. The tests provided examples of soft and hard-kill of UAVs caused by HPM impulses. Experimental findings show thresholds in filed magnitude above 50V/m were found to induce soft-kill effects, known as lock-up meant as permanently disruption of UAV systems. Furthermore, at intensities above 50kV/m, burnout effects were repeatable, primarily attributed to the thermal destruction of electronic components. Racer type UAVs, while hovering were subjected to HPM impulses. The expected distance between the antenna and the drones is around 100 meters; resulting in an estimated intensity of 3.7 kV/m. The UAV was exposed to exposure in a series of destructive tests. After opening the chamber, it was discovered that all four of the UAV's engines had ceased functioning. The issue was resolved by performing a reset by the removal and reinsertion of the battery. The UAV then underwent a second exposure. In this instance, the parameters of the generator were set for an infinite

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Research Article

quantity of pulses, and it was activated for duration of thirty seconds. Following the reopening of the chamber, the odor of smoldering plastic could be detected. The UAV exhibited a lack of responsiveness to external stimuli, with only two out of the four engines in operation. Upon the removal and subsequent reinsertion of the battery, the aforementioned motors exhibited immediate spinning upon the application of power, without any activation of the UAV. During the period of HPM exposure, the phenomenon of flashing or plasma generation was observed [21].

Impact of pulses on UAV

During tests conducted over the shooting range, the research achieved consistent UAV neutralization. Despite challenges in determining the exact cause of damages, whether due to direct radiation impact or subsequent fall, the presence of burnout effects was noted in three UAVs. The field intensity estimation affirmed the existence of substantial radiation levels across the range which wouldn't be lower than 3 kV/m, verifying the effective neutralization of the UAVs through HPM impulses. [21]

CONCLUSION

The increasing reliance on UAVs across various sectors necessitates robust countermeasures to address security risks and electromagnetic interference (EMI) threats. This study has explored the integration of high-power microwave (HPM) technologies, impulse radiating antennas (IRA), and electromagnetic pulse (EMP) systems for UAV detection, disruption, and neutralization. Through a comprehensive classification of intentional electromagnetic environments (IEME), we have identified key vulnerabilities in UAV sensor modules to electromagnetic attacks. The analysis of slotted waveguide arrays, helical reflectarrays, and circularly polarized reflectarrays highlights their effectiveness in counter-UAV operations, demonstrating their capability for directed energy applications. Furthermore, the implementation of dynamic geofencing and model predictive control (MPC) provides an additional layer of UAV flight restriction, enhancing security measures. Experimental studies and simulations validate the feasibility of integrating HPM-based directed energy weapons with advanced antenna configurations to achieve effective UAV mitigation. The findings of this research contribute to the evolution of next-generation drone defense systems, offering critical insights into the development of high-precision, energy-efficient and scalable security frameworks for both military and civilian applications. Future research should focus on enhancing power efficiency, increasing targeting precision, and expanding operational range to further improve the effectiveness of electromagnetic-based UAV countermeasures.

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Research Article

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