Radio Frequency Photonics:

Enabler of Electromagnetic Spectrum Dominance[1]

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Victory smiles upon those who anticipate the changes in the character of war, not upon those who wait to adapt themselves after the changes occur.[2]

Giulio Douhet
The Command of the Air (1921)

As Giulio Douhet proclaimed, the anticipation of a dynamic, complex, and evolving global environment is crucial to survival; no room exists for resistance to adapt or lack of preparedness.[3] The future undoubtedly holds multiple revolutionary changes. Focusing on technologies with the potential to produce a paradigm shift and also have strategic value can accelerate disruptive effects on the character of war. RF Photonics is an emerging technology that has the potential to revolutionize how the EMS is dominated. The path towards securing EMS superiority for the US requires significant investment in linking experts across academia, government, and industry. Removing duplicative EMS efforts across the services by integration and collaboration enables *appropriate* and fiscally responsible investments in enabling technologies. RF Photonics can lead the way in providing the necessary networked, agile, multifunctional, small and affordable, and adaptive or cognitive technologies that are required for JADC2 within an ABMS architecture.

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Introduction

The world operates in a continuum of electromagnetic radiation—energy of alternating electric and magnetic fields of various wavelengths traveling at $3x10^8$ m/s. This continuum of light is referred to as the electromagnetic spectrum (EMS). For the military, the "EMS is one of the most critical operational domains in modern warfare."[4] Many parts of the spectrum remain underutilized or entirely unused due to physical limitations in electronic circuits.[5] Expanding the use of EMS is not a new idea. The Department of Defense (DoD) identified in its 2013 Electromagnetic Spectrum Strategy, "all joint functions—including movement and maneuver, weapon engagements (fires), command and control, intelligence, protection, sustainment, and information are enabled by spectrum-dependent system (SDS) capabilities."[6] The path of SDS capabilities is growing exponentially and subsequently compounds the pace of EMS technological advancement. It is imperative for the US and its national security to remain the leader in EMS superiority.

Securing EMS superiority for the US requires significant investment in linking experts across academia, government, and industry to develop a strategic assessment of critical technologies that can lead to revolutionary EMS advancements. Innovation hubs, think tanks, and task-forces are prevalent in leading these assessments. The Air Force Warfighting Integration Capability (AFWIC) was formed because Chief of Staff Gen. David Goldfein identified the Air Force (AF) was "organized to perpetuate, not innovate."[7] AFWIC is charged with leading "enterprise-wide integration and future force design enabling the AF to rapidly transition into a networked, multi-domain 21st Century force."[8] An EMS dominance cross-functional team (CFT) exists because AFWIC recognizes the EMS is critical to the future multi-domain force. The EMS Dominance CFT will lead strategy development that pursues a holistic multi-domain approach across traditional lines of authority for EMS dominance while focusing on technologies to invest, divest, and drive process change. The success or failure of the US leading EMS superiority lies in identifying enabling technologies and pursuing an aggressive, collaborative investment to accelerate their advantages.

This research paper is designed to inform AFWIC of radio frequency (RF) photonics as an enabling technology for EMS superiority and consider investing in it as critical to the future force. In early 2019, the Electromagnetic Defense Task Force (EDTF) converged with the EMS Superiority Enterprise Capability Collaboration Team (ECCT) and identified the "preponderance of military forces is ill-prepared for an environment characterized by a degraded electromagnetic spectrum."[9] Brig. Gen. David Gaedecke led the ECCT team that characterized a vital aspect for securing EMS dominance is "re-instilling a culture of EMS awareness." Gen Gaedecke concluded, "superiority in the [EMS] is fundamental to the National Defense Strategy…we need to lead in research, technology and innovation. Superiority in the spectrum underpins all of these."[10] Gen Gaedecke is absolutely correct, multi-domain operations (MDO), multi-domain command and control (MDC2), Joint all-domain operations (JADO), and Joint all-domain command and control (JADC2), regardless the nomenclature, are reliant on the EMS to operate. If the AF and the Joint force expect to excel in future operational environments, the importance and awareness of the EMS cannot be taken lightly. The AF and partner services must assess and prioritize investments in enabling technologies. While RF photonics has existed since the 1970s, only recently has the technological base advanced to realize its advantages.[11] RF photonics is evolving and has the potential to revolutionize how the EMS is dominated.

This paper proceeds in three sections, (1) a discussion of why RF photonics is an essential enabling technology, (2) a summary of two initiatives leading the path forward, and (3) exploration of implications on ideas, organizations, and how to proceed. The first section provides an overview of what RF Photonics is, the evolving technological base, and its importance in a demanding, congested, and increasingly contested EMS environment. The second section highlights two in-development applications, the high-value airborne asset (HVAA) self-protection system, and the electronic attack (EA) resistant high throughput communication link. These applications identify significant advancements in EMS monitoring and maneuver and represent indications of future capabilities. The third section discusses why RF photonics stands out, relevance to the forthcoming all-domain operating concept, and advocacy for the unity of effort behind RF photonic capabilities.

An Overview of Radio Frequency Photonics

RF photonics, also known as microwave photonics, is the combination of RF electronics and optical photonics.[12] Photonics corresponds to manipulation of light or photons, whereas electronics is the manipulation of electrons.[13] RF photonics is typically divided into two classifications, (1) the use of photonic devices such as lasers, optical modulators, photodetectors, and optical fiber for the transport of RF signals, and (2) applying photonic techniques with optoelectronic devices in RF systems for processing.[14] Both underpin the evolution of RF photonics technology in the search for increased capabilities. The use of optical fiber for RF transport has significantly increased over the past few decades from its low-loss and available processing bandwidth, fueling the ever-increasing throughput demand in the telecommunication industry. This push for increased capability drives advancements in photonic devices, specifically the integrated photonic circuit (IPC), opening opportunities to replace or supplement the performance of limited electronic components.

Spectrum real estate below 20 GHz, where electronic components thrive, is becoming saturated and contested. As congestion grows, limitations in wireless throughput rise as neighboring signals become bandwidth constrained. RF photonics enables the transition to uncongested parts of the spectrum from its excellent high-frequency performance, high bandwidth capability, low transmission loss, immunity to electromagnetic interference, and low cost and weight.[15] Novel ideas of cognitive radio technology and dual-function radar-communications systems are being pursued to alleviate interference and limitations, but congestion still exists.[16] Expanding beyond 20 GHz to less congested areas of the EMS helps alleviate restricted maneuver and co-frequency sharing.

These higher frequencies, typically regarded as the millimeter-wave (mmW) band, opens opportunities for ultra-wideband signals, but the performance of traditional electronics at mmW frequencies is degraded and sometimes impracticable to design or build; conversely, RF photonics succeeds significantly in mmW and beyond. As industry and government recognize the inevitable congestion problem, the shift to mmW and beyond is well underway. 5G communication is targeting bands from 26-70 GHz, adversary state militaries are developing complex mmW low probability of intercept (LPI)/low probability of detection (LPD) signals, and investing in sophisticated passive detection technologies to span large bands of spectrum.[17] As the spectrum becomes more congested and contested, a literature review of RF photonics highlighted two focus areas where adopting and integrating RF photonic technology will help the future AF and DoD secure EMS dominance, (1) the IPC, and (2) the photonic phased array.

IPCs are analogous to their electronic cousin, the solid-state integrated circuit (IC). The early goal of the IC was to combine multiple discrete electronic components into one package to create efficiency in space and reliability. ICs have since evolved into the underlying enabler of every electronic device available today, from field programmable gate arrays, application-specific integrated circuits fueling blockchains, to sophisticated fire control radars. IPCs have the same goal, but to manipulate photons versus electrons. Akin to ICs and Moore's law, IPCs are on their way to accelerated advancements as academia and industry begin to realize their potential in wireless communications, signal processing, quantum information science, and neuromorphic photonics.[18] Figure 1 shows more applications the Air Force Research Laboratory (AFRL) identified IPCs could provide advantages over electronic equivalents.

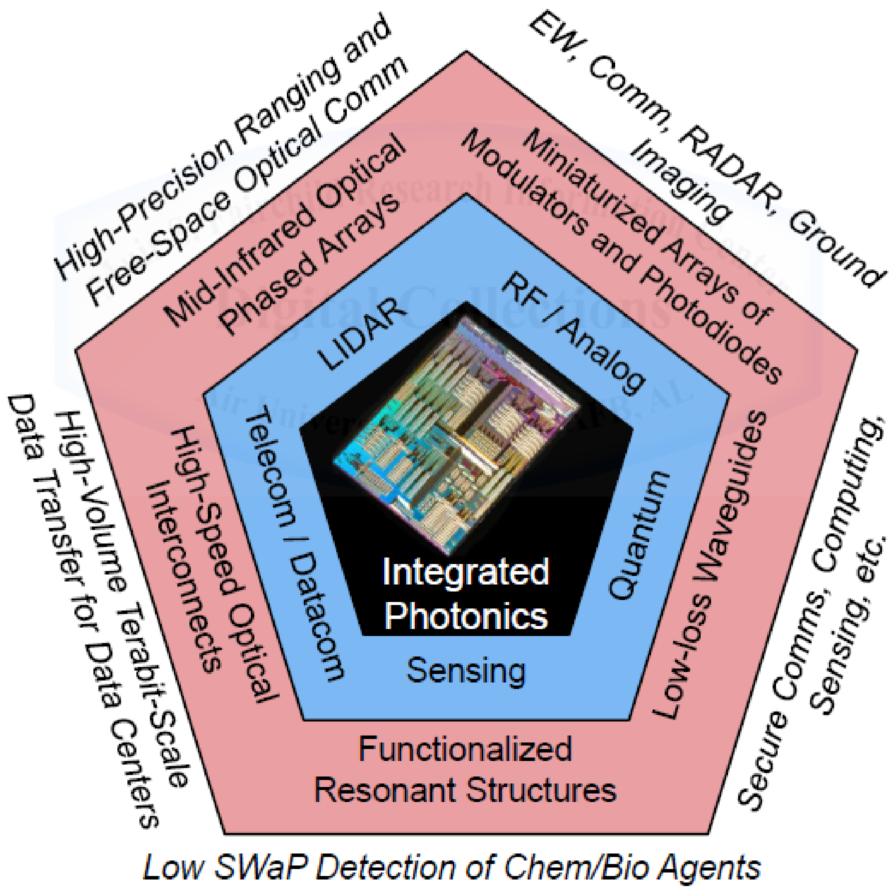

Figure 1. Integrated Photonics Applications[19]

The American Institute for Manufacturing Integrated Photonics (AIM Photonics) is enabling the IPC rise by stepping up to meet the demand for bulk IPC design and production. Similar to the IC semiconductor industry, IPCs require a design and fabrication process and the associated infrastructure to support mass production. AIM Photonics is the first in the world to create a process design kit, a multi-project wafer program, and infrastructure to support mass production at 300mm.[20] This manufacturing process is critical to advancing IPC research and development, allowing cost-effective access to industry. Déja vu to 1955 and the semiconductor industry, a parallel to how RF IPCs are a cornerstone of future EMS operations.

Along with IPCs, the photonic phased array is a crucial component of RF photonic systems that enables multiple advantages over electronic equivalents. Beam-steering and beamforming techniques are beneficial for high directivity and multifunction EMS applications. Phased arrays are the predominant way to implement these techniques and are becoming increasingly popular as 5G communication is deployed. Physical characteristics of the phased arrays are dependent on the intended maximum supported frequency. As frequency increases, the spacing between elements decreases due to the relationship to wavelength. For a phased array to accurately steer up to 90 degrees, the elements must be spaced less than half a wavelength apart, and at mmW frequencies, the spacing becomes very small. A 30 GHz signal requires less than one half of a millimeter spacing, making traditional electronics using coaxial cables impracticable. RF Photonics allows the use of fiber optic cables that are much smaller with inherent low-loss and immunity to electromagnetic interference (EMI), enabling superior design and meeting spacing requirements. Furthermore, phased arrays using IPCs enable much smaller designs and extremely low power draw, making them applicable to platforms that otherwise could not accommodate due to size, weight, or power requirements of purely electronic design.

Greater dependency on mmW spectrum is forcing the development of enabling technologies. RF photonics is evolving to allow significant advantages over electronic designs, specifically addressing size, weight, and power, including cost (SWaP-C).[21] These focus areas are increasingly relevant as the future force concentrates on JADO and JADC2. Research in IPC and photonic phased arrays draws attention to the overarching complex EMS environment and how to increase efficacy in military operations. Two in-development applications highlight advancements in EMS monitoring and maneuver and represent indications of a trend for future RF photonic capabilities.

In-Development Applications

Two applications currently being pursued at AFRL are the high-value airborne asset (HVAA) self-protection system and the electronic attack (EA) resistant high throughput communication link.[22] Both of these applications provide enabling capabilities for EMS superiority and introduce novel architecture to perform outside electronic strategies. Additionally, both applications integrate and leverage industry with academia to further conceptual development of the available technological RF photonic base.

AFRL is working with Phase Sensitive Innovations Inc. (PSI) and Georgia Tech Research Institute (GTRI) to develop an automated system that can detect and respond to multi-axis threats covering large bandwidths. Current large HVAAs such as tankers, ISR, and C2 platforms lack maneuver agility that renders them susceptible to multi-axis threat engagements.[23] As threats move to more advanced RF guidance systems, the use of mmW frequencies and multi-axis attack vectors drives the complexity of electronic support, electronic protection (EP), and EA systems that can give timely threat notification and reaction. PSI is designing an imaging phased array frontend that can survey an instantaneous bandwidth of approximately 50GHz over a 90-degree azimuth field of view with angle discrimination of 1-2 degrees for greater than four simultaneous threats. These performance characteristics are only obtainable by using RF photonics. The imaging phased array is driven by a photonic analog imager that provides an "unambiguous angle of arrival and frequency information fast enough" for an autonomously managed EA/EP response.[24]

Efficient cueing of the defensive countermeasures is critical to HVAA survival as the timeline for threat launch to impact is typically less than 20 seconds. Advanced threat signals employ LPI/LPD features, such as changing frequency, pulse repetition interval, and power level to lower its probability of intercept (POI). Traditional digital beamforming phased array systems can only provide 500 MHz of instantaneous bandwidth and therefore requires a scanning receiver to span an extensive frequency range.[25] Scanning for a LPI/LPD threat significantly reduces POI and subsequent reaction. The photonic imager is not affected by LPI/LPD techniques since it is continuously observing the entire frequency band. GTRI is developing the backend integration and processing with EP/EA capabilities. Once cued by the photonic imager, the autonomous countermeasure manager can provide on-board EA to deny detection and track along with angle deception and home-on-jam capabilities through a launched decoy. Figure 2 illustrates the RF Photonic system anticipated for Phase I demonstration.

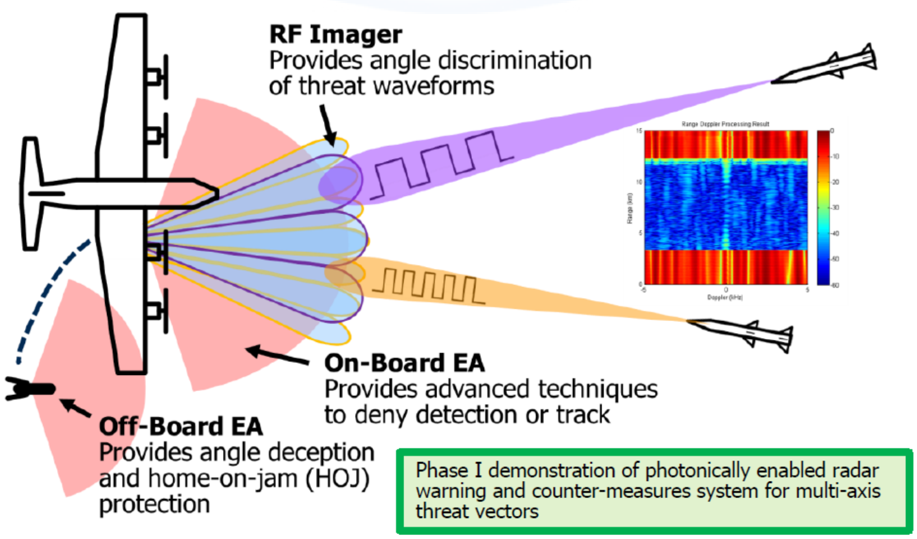

Figure 2. RF Photonic HVAA self-protection system[26]

AFRL is also researching RF photonic phased arrays for applications in communications. Unique to a photonic phased array is the ability to have multiple data streams on a single steerable beam simultaneously without splitting the total system bandwidth between each beam. This multifunction steerable beam allows tremendous bandwidth capability, resiliency, simultaneous capabilities, and security to a communication link. Experiments have shown the photonic phased array can handle two communication links simultaneously, a 4 quadrature amplitude modulation (QAM) signal and a 16 QAM signal without degradation. Other experiments tested the communication link in the presence of a jammer, and simultaneous radar functions without interference.[27] As the level of QAM increases, enabling higher data rates, traditional QAM links are susceptible to noise due to the spacing of constellation elements. However, in RF photonic phased arrays, the experiments showed lowered noise susceptibility in the presence of other signals. While IPCs and photonic phased arrays show a promising future, to leverage their significant advantages over traditional electronics that the AF and DoD can use to advance superiority lies in the commitment to understand the criticality of investment and unity of effort between industry, academic and government organizations now.

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Implications for the Future

EMS superiority is defined as the "degree of dominance in the electromagnetic spectrum that permits the conduct of operations at a given time and place without prohibitive interference while affecting an adversary's ability to do the same."[28] The degree of dominance necessary is contextual, but regardless of the situation, it is only achievable by the underlying enabling technology, employment of it, and education behind it. The National Defense Strategy states, "[we] cannot expect success fighting tomorrow's conflicts with yesterday's weapons or equipment."[29] The impetus is not just recognizing technology that can shift the paradigm in how the strategic environment is shaped and subsequently operate in, but to operationally and tactically change with it. While there is undoubtedly a level of subjectivity in identifying enabling technologies, as the technology matures, a balance of evidence starts to show trends that lead to the eventuality of its importance. As the AF shifts towards MDO, the operating concept requires a source agnostic sensing grid, resilient communications, advanced battle management system (ABMS), and convergence in all domains.[30] These all require use of the EMS where IPCs and photonic phased arrays can have significant influence.

The aforementioned main advantages of RF photonics are directly related to SWaP-C. Building a sensing grid will require infrastructure that can handle massive amounts of data throughput along with sensors that can timely gather the information. Fiber optical backhauls for the telecommunication industry have been a staple of fast and resilient wired networks that remain a critical piece of infrastructure. The benefits of fiber optic data throughput in the wired domain are not easily transitioned to the wireless domain. As 5G communication is stood up, industry is turning to RF photonics for help.[31] IPCs and photonic phased arrays can provide the necessary subsystems to build a source agnostic, resilient, high data throughput wireless sensing and communication grid. Traditional systems operating at mmW and beyond frequencies require bulky, heavy, power-hungry discrete electronic components that down-convert to lower frequencies so processing with an electronic subsystem is possible. These systems unavoidably add noise, potentially removing useful signal information in the process.[32]

IPCs and photonic phased arrays eschew inherent electronic system limitations, enabling manipulation of complex high-frequency and large bandwidth RF signals while maximizing reductions in SWaP-C. Morton Photonics is proving the significant reductions in SWaP-C with its Simultaneous RF Beamforming Phased Array Sensors through Wafer Scale Photonic

Integration (SimBeam) program.[33] SimBeam is intended to build "a new generation of [IPC] enabled Receive Phased Array Antenna (Rx-PAA)…with unique capabilities not obtainable with electronic-only systems, and with significantly lower size, weight, and power."[34] The Rx-PAA system is envisioned for unmanned aircraft systems (UASs), as well as other DoD assets, including manned aircraft, space platforms, ships, and land vehicles. This initiative is indicative of a platform-agnostic distributed senor capable of attaining an intelligence preparation of the EMS environment, while simultaneously providing infrastructure for advanced battle management to an All-Domain Ops Center (ADOC) and employing multi-axis EA in an AOR. While this description is theorized, the enabling technology exists, and with it drives adjustments to the way the AF and the DoD fight.

I.B. Holley illustrates in his seminal book, *Ideas and Weapons*, a struggle still evident today: innovation is elusive, and military technological transformations are complexly shaped by the institution and the bureaucracy within. Holley states three shortcomings inhibit progress towards superior military advantage, "a failure to adopt, actively and positively, the thesis that superior arms favor victory; a failure to recognize the importance of establishing a doctrine regarding the use of weapons; and a failure to devise effective techniques for recognizing and evaluating potential weapons in the advances of science and technology."[35] It is arguable that Holley's first shortcoming is of his time in writing and does not adhere well to adversaries of today that lack technological advance yet fight with sophistication. More likely, the importance lies in the *effectiveness* and contextual adaptability or employment of the technology. The other two shortcomings are still evident today. While the doctrinal process has improved by providing "doctrine notes as a bridging solution to a potential doctrine void,"[36] it is still bogged down in bureaucracy, and the operational/tactical level hardly sees a debate worth the effort to try and enhance it. Agencies like the Defense Advanced Research Projects Agency (DARPA) were stood up because of Holley's third shortcoming, yet after 62 years, it seems there is still a lack of unity behind understanding implications of technological advancements that inhibits *appropriate* investments. Unity of effort is a crucial element, and a shared understanding of emerging EMS concepts and innovation among all DoD services, national agencies, and industry is required.

Recently, AF doctrine on EMS operations was updated to change all references to 'electronic' to 'electromagnetic'; for example, instead of electronic warfare, it is now electromagnetic warfare.[37] This change illustrates the importance of a common lexicon when discussing EMS operations; Joint doctrine has not yet made the change—there is an impetus for Joint, but a lack of actual unity. Each service has its own doctrine development center in addition to joint doctrine, and rightly so since each service has a distinct warfighting domain, but the EMS is not distinct to one service, as is the same with cyber and information operations. As Holley would argue, the institution inhibits unity since each service is narrowly focused on understanding how to use the EMS in their domain. While this is a broad claim and overarching issue, it still carries impact for the adoption of IPCs and photonic phased arrays, as each service will try to push and pull to their advantage or specific application versus collaborating on an advancement that can adapt and scale for multiple applications. An article published by the Center for Strategic and International Studies concluded that the DoD faces risks concerning the EMS in disjointed efforts: "the DoD fails to unify [EMS technological] efforts, allowing stove-piped training and capability development to continue. This results in a diminished ability for the joint force to organize, train, and equip in [electromagnetic] warfare."[38] Disjointed efforts often result from a lack of awareness of the other party and overzealous assumptions of what others are doing. While the DoD envisions a simplistic ecosystem for jointness and innovation, it is quite the opposite and very complicated.[39] In this context, *complicated* is specifically chosen—the distinction between complicated and complex matters, see *Team of Teams*.[40] There is no requirement for every Airman to understand the intricacies of the EMS or the DoD innovation ecosystem; the value is within the Airman's awareness of it.

A search for 'Electromagnetic Spectrum' in the Joint Electronic Library Plus reveals 231 authoritative joint doctrine publications that reference EMS.[41] Add each service's EMS doctrine, and it becomes hard to keep track of what the actual message is. Holley defines doctrine as "what is taught…rules or procedures drawn by competent authority…precepts, guides, to *action*, suggested methods for solving problems or attaining desired results" (emphasis added).[42] While it is understood that each service has specific functions and therefore teach within their specific context, the EMS spans all operational domains, and therefore education and awareness of it are inherently joint. The implication is a more simplistic structure enables emerging EMS technologies to pair with a doctrinal framework and either push a technological advance or pull doctrine into a new and unanticipated arena.[43] The fielded force is what drives the doctrinal continuum, with *action,* observation takes place to develop a concept that is put to the test to either form doctrine or put back in the cycle.[44] IPCs and photonic phased arrays can be transformative if the fielded force is aware and can provide feedback on what are essential capabilities. Holley makes this evident through an analysis of Russian military doctrine development: "perhaps nowhere is this more pointedly expressed than in a Russian military study by two Soviet officers, Druzhinin and Rontorov, entitled…*Concept, Algorithm, Decision*, 'development…is possible only in the presence of contradictions. The absence of contradictions signifies…stagnation. The detection and disclosure of contradictions is the discovery of causes that give rise to progress.'"[45] In the use case of SimBeam, the fielded force can perform multifunction EMS operations with one sensor, scaling the capability to advanced levels of collaboration while also allowing agility for the sensor network. The operator can make the observation of necessary force structure and adapt to the changing operational environment. Desired end states shape the tools and organizational structure that allows efficacy in the doctrinal continuum. In essence, it starts with challenging the current doctrine and raising awareness of emerging technologies that enhance fielded forces.

A study on decision-centric operations conducted by the Center for Strategic and Budgetary Assessments (CSBA) concluded: "combination of disruptive technology and revolutionary operational concept created significant innovations…result[ing] in new competitive regimes."[46] As seen in Figure 3 (purple, bottom right square), a revolutionary and disruptive paring of technology and operational concept encounters significant institutional resistance. The AF is pursuing a new operating concept, MDO, and hierarchically at the Joint level, JADO, involving a significant change in operating concepts. Enabling disruptive technologies, such as RF photonic, can lead the way to redefine performance metrics and establish a new competitive regime.

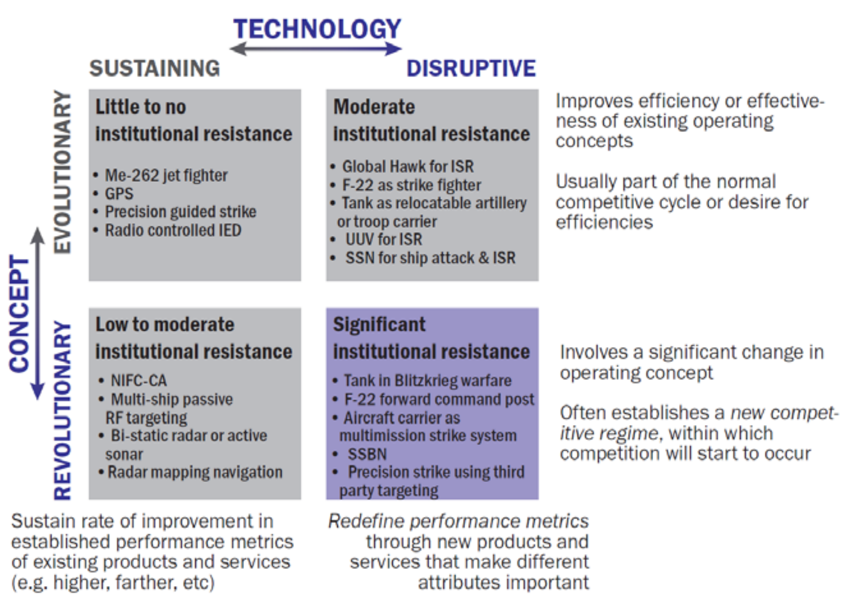

Figure 3. Transformative Military Technologies[47]

CSBA also conducted a study on EMS spectrum dominance that proposed over the years electromagnetic warfare has shifted in phases, and the current one is "low-to-no power" EMS warfare.[48] IPCs and photonic phased arrays are capable of providing these "low-to-no-power" sensors that enable new operational concepts. The study also pushes investment in networked, agile, multifunctional, small and affordable, and adaptive or cognitive technologies.[49] All of these features can be enabled by IPCs alone or paired with a photonic phased array as the underlying technology. Subsequently shown in Figure 3, emerging technologies will drive new operational concepts that potentially require significant changes in force structure by more integration of currently separate but parallel organizations that will resist. There is no room for resistance to adapt or lack of preparedness; the future undoubtedly holds multiple revolutionary changes. Focusing on technologies with the potential to produce a paradigm shift and also have strategic value can accelerate disruptive effects on the character of war. Integrating and removing duplicate efforts provides the efficacy to find these technologies.

The path towards securing EMS superiority for the US requires significant investment in linking experts across academia, government, and industry. Holley suggests that transformative military technological advancement relies heavily on knowing and partnering with industry.[50] Take it one step further and add academia. While there are already numerous methods the AF and DoD are linked to industry and academia, it seems overly complicated and duplicative.[51] Similarly, removing duplicative efforts between the services is also necessary. Not only would it reduce cost, but it also provides a more holistic approach to field more networked, agile, multifunction capabilities essential to future EMS warfare operations. RF Photonics is on a path to disrupt future EMS operations and enable JADO and underlying ABMS inter-service MDO; the sooner *action* is taken to collaborate, increase awareness, invest, define new operational

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concepts, and employ them, the more significant edge the AF and DoD will have in the EMS. "What is revolutionary is not the *speed* with which the change takes place, but rather the *magnitude* of the change itself" (emphasis added).[52] The preparedness of a nation's ability to maintain a competitive advantage and assert itself rests in its technological base and the understanding of the strategic value it brings.

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Notes

[1] I give appreciation to my family and Dr. Paul Hoffman for their humble review and input. All errors within are my own., May 6, 2020.
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