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PERSPECTIVE

Electromagnetic protection strategy using adaptive energy selective mechanism

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Electromagnetic spaces face growing threats from both naturally occurring and artificial electromagnetic pulses; however, the current protection methodologies are still far from practical needs. To address this issue, we propose an electromagnetic protection strategy that makes use of an adaptive energy selective mechanism. This strategy, carried out using electromagnetic metamaterials, provides in-band protection to electronic equipment with a high tolerance threshold and fast response. We propose several approaches to further enhance the protective performance of electromagnetic metamaterials. These include reconfigurable designs based on digital circuits and deep learning algorithms, as well as the adoption of nanoscale field-controlled devices made of two-dimensional (2D) phase transition materials and nanoelectromechanical systems. Our study can not only lead to a comprehensive protection system with superior compatibility, but also offer reliable support for maintaining electromagnetic spatial security.

An electromagnetic pulse (EMP), also called a transient electromagnetic disturbance, is a short burst of electromagnetic energy. The origin of EMP can be natural, such as lightning, electrostatic discharge, and coronal mass ejection, or artificial, such as power line surges, switching pulses, and high-power microwaves. Electromagnetic interference generated from EMPs can damage and even destroy electronic equipment, causing irreversible disruption in communicating platforms such as radar, aircraft, communication base stations, and navigation satellites.[1] Until now, globally, concerns have been raised regarding efficient protection methodologies against EMPs, prompting the implementation of relevant rules and protocols in Europe (European project structures, 2014), the United States (Electromagnetic Pulse Resilience Action Plan, 2017), and China (Law of the People's Republic of China on National Defense, 2020). Developing a comprehensive protection system is an urgent requirement to maintain the stability of electromagnetic space, and further preserve information security at the national strategic level.

EMPs produce damaging surges and currents in electronic devices through "front door" coupling paths such as antennas and transmission lines, as well as "back door" coupling paths such as ventilated openings and cables. These paths can be cut off using conventional technologies, such as shielding, absorbing, and grounding. However, high-level EMP signals generally exhibit the characteristics of extremely high strength (>10 kV/m), short pulse rising edge (∼1 ns), and ultra-wide spectrum from the megahertz (MHz) to terahertz (THz) regime, thereby making the commonly utilized protective components invalid in most cases. For instance, filters and isolators cannot provide effective in-band protection, whereas limiters have a maximum withstanding threshold of 2 kV/m.

From this perspective, we introduce a promising method of electromagnetic protection using an adaptive energy selective mechanism that enables good compatibility with electronic systems in complex electromagnetic environments (Figure 1). This mechanism is implemented using a novel type of impedance-tunable electromagnetic metamaterial, in which the incident wave can be automatically reflected once its energy exceeds a set threshold. We investigated several approaches for structural optimization and design to further enhance the protective performance of metamaterials.

ADOPTING ENERGY SELECTIVE MECHANISM

Considering that the major distinction between normal communication and high-level EMPs is the amount of energy carried in electromagnetic waves, we propose the concept of an energy selective mechanism as depicted in Figure 1A. Based on the external field strength, safe signals can be smoothly received by electronic devices with a negligible insert loss ($S_{21} > -1$ dB), whereas EMPs are reflected with a high shielding effectiveness ($S_{21} < -20$ dB) to minimize their destructive effects. The feasibility of this mechanism has previously been investigated through theoretical and experimental studies by our research group. A unique electromagnetic metamaterial, an energy selective surface (ESS), was investigated to achieve this mechanism with adaptive capability. In principle, an ESS is composed of three functional components. The matching layer is used to match the impedance between the ESS and free space, and the induction layer evaluates the spatial field strength. The impedance layer consists of a periodic metal-resonant frame and field-controlled devices (PIN diodes), and exhibits impedance tunability dominated by the external field strength. Under normal communication, the ESS has high impedance and thus, allows signals to transmit with a sufficiently low insertion loss. However, when EMPs are incident, the ESS performs low impedance attributed to the conduction of PIN diodes, leading to significant attenuation of EMPs.

DESIGNING RECONFIGURABLE METAMATERIALS

Similar to the well-studied frequency selective surface (FSS), the performance of an ESS can be controlled by structural design of the metal-resonant frame. For example, our group realized an ultra-broadband ESS from 5.45 to 13.8 GHz by an equivalent model, with an insertion loss <0.5 dB and shielding effectiveness >20 dB.[2] Additionally, Zhou and Shen[3] achieved dual-resonance protection at approximately 3 GHz using a sandwich ESS combined with an FSS. However, limitations posed by the operational bandwidth and losses can be magnified on introducing more complicated RC circuits in the design procedure. In addition, achieving tunable performance of metamaterials remains an open problem, with several challenges from both theoretical and technological viewpoints.

Reconfigurable metamaterials can remarkably modulate their electromagnetic characteristics by controlling the active components inside, making them more flexible for electromagnetic protection.[4] To realize reconfigurability of an ESS in a wide range, we mainly propose two approaches, as illustrated in Figure 1B. First, inspired by previously reported programmable metamaterials,[5] ESSs can operate together with back-side digital circuits, from which a sequence of "on/off" ("1/0") commands is sent to the ESS, which thoroughly controls the PIN diode array to tune its resonance and phase. Second, deep learning algorithms can be employed to enable inverse construction from the desired operating band (input) to the "on/off" commands of digital circuits (output I), as well as the geometric shape of the metal-resonant frame (output II). As an increasingly employed optimization technique in recent research,[6] deep learning offers more degrees of freedom in the structural design of metamaterials. Equivalent circuit analysis, computational simulation, and experiment can expand the training database, so as to increase the accuracy and suitability of learning process. In addition, it is of interest to develop multi-objective and constrained algorithms that can arrange the path reasonably and promote learning efficiency.

ADVANCING 2D MATERIALS DEVICES

We now focus on alternatives for PIN diodes employed as field-controlled devices in ESS. The rapid development of ultrasensitive materials and structures at the nanoscale has opened new opportunities for breakthroughs in electronic devices. For example, Samizadeh et al.[7] investigated a novel on-chip, all-electronic device based on nanoplasma that enabled picosecond switching of

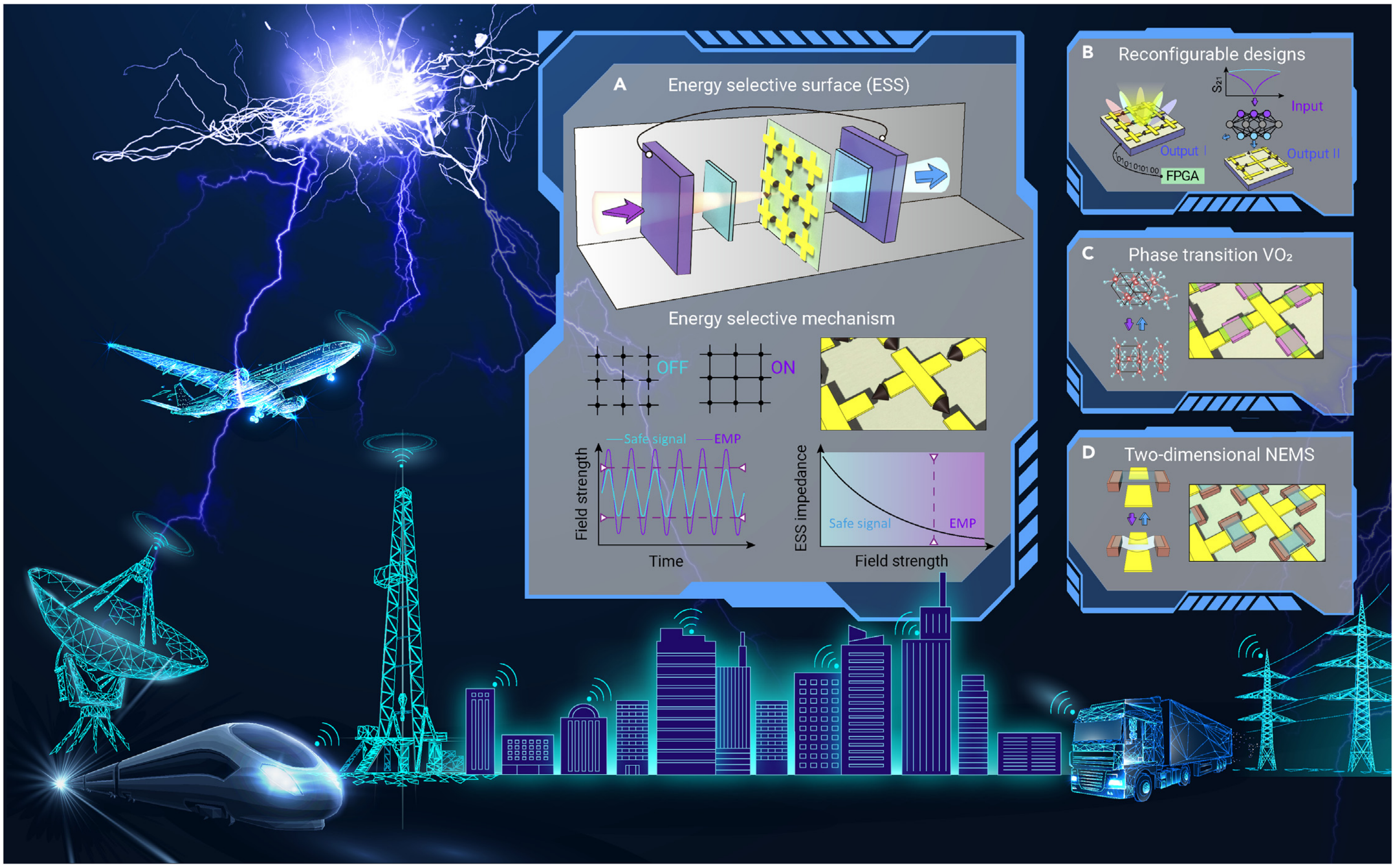

Figure 1. Framework of the proposed protection strategy against electromagnetic pulses using adaptive energy selective mechanism (A) Adaptive energy selective mechanism. (B) Reconfigurable designs on electromagnetic metamaterials. (C) and (D) Phase transition VO_2 and 2D NEMS using as field-controlled devices, respectively.

electric signals with a wide range of power levels. Two-dimensional materials, such as monolayer graphene, have extraordinary potential for both fundamental studies and advanced applications. The Fermi level of 2D materials can be altered to obtain gate-controllable light-matter interactions. Although many studies have been devoted to the application of 2D-based reconfigurable metamaterials for dynamic tuning of incident waves in the THz regime, 2D materials are still not valid for protection against EMPs because of their weak response to microwaves.

Considering the dramatic thermal effect generated by EMPs when coupled with electronic devices, we focused on the thermal properties of 2D materials rather than their optical absorption. Interestingly, vanadium dioxide (VO_2) undergoes a phase transition from an insulating (transmission) to a metallic (shielding) state at approximately 341 K, exhibiting a three-order-magnitude variation in electrical conductivity.[8] This feature makes VO_2 nanosheet a prime candidate for field-controlled devices in ESS. The critical transition temperature of VO_2 can be regarded as the threshold temperature between the transmission and shielding states (see Figure 1C). To accelerate the switching (transition) process, VO_2 can be combined with an insulating layer of hexagonal boron nitride (h-BN) on top, with a thermal conductivity that is sufficiently high for fast energy dissipation.

Nanoelectromechanical system (NEMS) devices composed of suspended 2D membranes possess the merits of minuscule dimension, high tunability, and distinctive features, which are appealing for nanoscale sensing applications.[9] Therefore, 2D NEMS can also replace as field-controlled devices in ESS (see Figure 1D). At room temperature, the gap between the suspended 2D membrane and bottom metal substrate forms a capacitance, resulting in the transmission state of ESS due to the disconnection of metal grids. As the temperature increases by EMPs, suspended 2D membrane bends downward attributed to a thermally induced compression from boundary.[10] ESS changes to its shielding state once the membrane touches the metal-resonant frame. The threshold depends on the initial deflection of the membrane, which can be modified by applying a pre-bias voltage.

Compared with PIN diode arrays, 2D material devices have a longer lifespan and higher sensitivity to their surroundings, which can considerably boost their reliability when used as field-controlled devices. More importantly, the unit size of ESS is reduced to nanoscale as the operating band increases to THz and near-infrared regimes. As a consequence, at such a small scale, 2D material devices would better match with the required structural design compared with PIN diode arrays. Further studies will focus on experimental demonstrations of 2D-based ESS, as well as improvements on their switching speed and tolerance threshold.

CONCLUDING REMARKS

In this perspective, we propose an electromagnetic protection strategy for electronic devices and systems against EMPs. The employed energy selective mechanism shows better compatibility and adaptivity than other kinds of protection methodologies. Pathways have been offered for improving the protective performance from two aspects: (1) designing reconfigurable metamaterials combined with back-side digital circuits, while adopting deep learning for structural optimization; and (2) replacing PIN diode arrays with 2D phase transition materials and NEMS devices as field-controlled devices in metamaterials. Our strategy not only contributes to the fundamental understanding of metamaterials and nanoscale functional structures, but is also significant for building comprehensive electromagnetic protection and preserving national information security.

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DECLARATION OF INTERESTS

The authors declare no competing interests.