Information metasurfaces and intelligent metasurfaces

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Metamaterials, due to their incomparable capabilities in manipulating effective material parameters, have been attracting worldwide attention in the past two decades. In previous works, most metamaterials and metasurfaces focused on the material parameter steering in a continuous scale, which is regarded as "analog metamaterials/metasurfaces." Since Cui *et al.* proposed the concept of digital coding and programmable metamaterials/metasurfaces in 2014[1], a new perspective to design metasurfaces has been opened up, bridging between electromagnetic physics and digital information for the first time. Coding metamaterials/metasurfaces have presented diverse physical principles and applications in electromagnetic field manipulations, further deriving many subdirections. In the process of exploration and enrichment in recent years, the coding metasurface has continuously demonstrated its powerful ability in information regulation and combination. Using this as a strong connection, the field has gradually grown into a new system called information metamaterials/metasurfaces[2,3].

In their recent review article[4], Ma *et al.* provide an overview of information metasurfaces and intelligent metasurfaces, starting from the concept and theories of coding metasurfaces, like convolution operations[5] and information entropy theory[6]. To extend the capability of coding metasurfaces, programmable metasurfaces have been proposed with various application scenarios such as reprogrammable plasmonic topological insulators[7], space-time-coding metasurfaces[8], and space- and frequency-multiplexing wireless communication systems[9]. These programmable designs have explored new degrees for modulating waves, controlling the frequency spectra, and increasing the information capacity. Since artificial intelligence (AI) has become more important in automatic designs, Ma *et al.* also provide an overview of intelligent design of metasurfaces, including the designs of meta-atoms and atom-arrays. Among all the mentioned intelligent design methods in Ref. [4], the supervised deep learning methods, including the prediction neural networks and inverse neural networks, present high efficiency and accuracy. However, the huge degree of dependence on the training data extremely limits the popularization of these supervised methods. Ma *et al.* give the case of adding physical mechanism into the construction of neural network structures and realizing unsupervised learning[2], which results in a great reduction for the demand of training data. In our opinion, the deep combination of physical mechanism and artificial intelligence would be a growing development tendency for the intelligent designs of metasurfaces, which could increase the interpretability of relevant deep learning methods and lower the threshold for data preparation.

Among the variety of works mentioned in this review[4], we would like to discuss one of the most intriguing, from our point of view: the programmable artificial intelligence machine (PAIM)[10]. The PAIM is a physical realization of diffractive deep neural networks (D^2NNs). The concept of all-optical D^2NN was first realized by Lin *et al.* with multi-layer cascade metasurfaces[11]. This physical computing hardware can instantly solve large-scale matrix calculation as the light passes through the metasurfaces, yielding apparent advantages over traditional chips and computing hardware in terms of computing speed and energy efficiency. PAIM extends the concept to the digital domain by making the all-optical D^2NN programmable. By means of dynamic adjustment for the states of artificial neurons made of meta-atoms, the PAIM can appropriately switch its functions among image recognition, mobile communication coding-decoding, and real-time multi-beam focusing. We believe that these demonstrated functions are far from the maximal capacity of PAIM and there is still huge potential to increase the integration level and number of artificial neurons of PAIM, even reaching an all-optical version of PAIM.

Information metasurfaces have been gradually becoming a comprehensive research hotspot linking multiple disciplines, injecting new vitality into physical electromagnetics and artificial intelligence research. It is foreseeable that the information metasurface will deeply influence the future development of new electromagnetic devices, as well as new optical intelligent computing hardware.

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