Coding Metamaterials and Programmable Metamaterials

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Metamaterials

- Physics Community: **New Physics**
- EE Community: - **Follow the Work from Physics**
  - **Engineering & Applications**
  - **New Views from Information Science**

- Coding and Programmable
- Effective Media
- Surface Plasmonics

Metamaterials
Background: Effective Medium

Cloaks

New Lenses

New Physics

New Applications

EM Black Hole

Random Metasurface


New Physics

New Lenses

New Applications
Background: Metasurfaces

Surface Waves

Spatial Waves


APL, 2013

Tensor Metasurface

Background: Surface Plasmonics

Flexible SPPs

LSPs

PNAS, 2013.

A Lot of Passive Components.

Active SPP Components:


ACS Photonics, 2015.


Background: Surface Plasmonics

Interference Reduction


Multi-Layered Circuits

Antenna and System

ACS Photonics 2015.

APL, 2015.
Background: Our Motivation

- To make instant or real-time controls of EM waves by metamaterials
- To realize significantly switchable functionalities using a single metamaterial
Circuits

- Analog Circuits: Continuous currents
- Digital Circuits: People use the coding of 0 and 1 to process information.

Metamaterials

- The current metamaterials are based on continuous medium parameters, which can be considered as analog metamaterials.
- We propose the concept of coding metamaterial, which can be further extended to programmable metamaterial.
Coding Metamaterials

1-Bit Coding Metamaterials

- Control EM waves by changing the coding sequences of 0 and 1 units

- 0 Unit: 0 Phase
- 1 Unit: 180 Phase

Cui et al., Light: Science & Applications 3, e218; 2014
Coding Metamaterials

**Basic Element**

\[ a = 5 \text{ mm}, \quad h = 1.964 \text{ mm}, \quad t = 0.018 \text{ mm}, \quad w = 4.8 \text{ mm} : \text{0 Unit} \]

\[ w = 3.75 \text{ mm} : \text{1 Unit} \]

Realization of 0/1 Unit Cells
The radiation and scattering patterns can be controlled by coding the 0 and 1 elements:

\[ f(\theta, \varphi) = f_e(\theta, \varphi) \sum_{m=1}^{N} \sum_{n=1}^{N} \exp\{-i\{\varphi(m, n) + kD \sin \theta[(m - 1/2) \cos \varphi + (n - 1/2) \sin \varphi]\}\}, \]

\[ \text{Dir}(\theta, \varphi) = 4\pi |f(\theta, \varphi)|^2 / \int_0^{2\pi} \int_0^{\pi/2} |f(\theta, \varphi)|^2 \sin \theta d\theta d\varphi. \]

Solving the inverse problem, given arbitrary wave patterns, we can design the corresponding coding sequences of 0 and 1 elements.
The optimized codes for different lattice numbers $N$

<table>
<thead>
<tr>
<th>N</th>
<th>Code Sequence</th>
<th>RCS Reduction (dB)</th>
</tr>
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<tbody>
<tr>
<td>6</td>
<td>001011</td>
<td>-12.08</td>
</tr>
<tr>
<td>7</td>
<td>0011010</td>
<td>-14.64</td>
</tr>
<tr>
<td>8</td>
<td>00110101</td>
<td>-15.82</td>
</tr>
<tr>
<td>10</td>
<td>0001010110</td>
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<tr>
<td>12</td>
<td>001001110101</td>
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<td>14</td>
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<td>16</td>
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<td>-22.37</td>
</tr>
<tr>
<td>20</td>
<td>01000100110000110101</td>
<td>-23.58</td>
</tr>
</tbody>
</table>
1-Bit Coding Metamaterials

1-Bit Coding Metasurface for RCS Reduction
2-Bit Coding Metamaterials

2-Bit Coding Metamaterial - Four Basic Elements

“00” – 0; “01” – 90; “10” – 180; “11” – 270
2-Bit Coding Metamaterials

“00” “01” “10” “11” Sequence: Gradient Phase

Generalized Snell’s Law

Capaso’ Grp, Science, 2011
Zhou’s Grp, Nat. Mater., 2012
Better performance is observed for RCS reduction using 2-bit coding metamaterial
Digital Metamaterials

- Coding metamaterials are not our final purpose
- We aim to realize digital control of coding sequence

This is a purely theoretical work.
The “digital” here in fact means “discrete”.
Our concept is proposed independently, and has totally different meaning: digitally control
A unique metamaterial particle, which can be either 0 or 1, controlled by the pin diode.

- We can control the state of each particle as 0 or 1 by giving two different biased voltages.
- We can then control the coding sequences of 0 and 1.

The Phase Responses

Cui et al., Light: Science & Applications 3, e218; doi:10.1038/lsa.2014.99, 2014
By using field-programmable gate array (FPGA) hardware, we realize digital control over the digital metamaterial. We can write a program consisting of many cases onto FPGA, which is used to control many functionalities in real-time: Programmable Metamaterial.
Programmable Metamaterials
Experimental Validation

- A Simple Example:
- Six-Code Sequence
- Many functionalities can be realized by a single metamaterial, which are switched in real time, and computer controllable.

Cui et al., Light: Science & Applications 3, e218; 2014
New-Concept Radar

2D Programmable Metasurface

New-Concept Radar:
- Single Beam
- Multiple Beams
- Beam Scanning
- RCS Reduction

New Imaging System

Radar Imaging: Phase Array; Mechanical Scanning (SAR)

Single-Radar Imaging

Diffusion
Metasurface
Frequency Diversity
Object Dispersion

Metamaterial Apertures for Computational Imaging
John Hunt et al.
Science 339, 310 (2013);
DOI: 10.1126/science.1230054

Cummer’s Grp:
Acoustic, PNAS 2015
Padilla’s Grp:
THz, Nat. Phot. 2014
New Imaging System

The object in the far-field

Transmission pattern

2-bit Transmit-Type Programmable Metasurface

Single-Radar and Single-Frequency Imaging System

Li et al., Sci. Rep., 2015
New Imaging System

\[
\begin{bmatrix}
E_1 \\
E_2 \\
\vdots \\
E_N
\end{bmatrix}
= 
\begin{bmatrix}
G_{11} & G_{12} & \cdots & G_{1N} \\
G_{21} & G_{22} & \cdots & \vdots \\
\vdots & \vdots & \ddots & \vdots \\
G_{N1} & \vdots & \cdots & G_{NN}
\end{bmatrix}
\begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\vdots \\
\sigma_N
\end{bmatrix}
\]

Inverse-Scattering Theory

Generalized System Response Matrix

Li et al., Sci. Rep., 2015
New Imaging System

Li et al., Sci. Rep., 2015
Terahertz Coding Metasurfaces

A novel coding particle: Minkowski fractal structure

1-bit, 2-bit, and 3-bit coding particles can be realized using the Minkowski loops with different scales

Design of Coding Particles

Designs of the Minkowski coding particles

![Graphs and table showing the design of coding particles]

<table>
<thead>
<tr>
<th>Multi-bit</th>
<th>Shape &amp; Phase</th>
<th>0</th>
<th>-45</th>
<th>-90</th>
<th>-135</th>
<th>-180</th>
<th>-225</th>
<th>-270</th>
<th>-315</th>
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<tbody>
<tr>
<td>1-bit</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-bit</td>
<td>00</td>
<td>01</td>
<td></td>
<td></td>
<td></td>
<td>10</td>
<td>11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-bit</td>
<td>000</td>
<td>001</td>
<td>010</td>
<td>011</td>
<td>100</td>
<td>101</td>
<td>110</td>
<td>111</td>
<td></td>
</tr>
</tbody>
</table>
Abnormal THz Reflections

The scattering features of periodic arrangements of coding particles. (a) The 1-bit coding with all “1” elements. (b) The 1-bit coding with the chess-board “0” and “1” distribution. (c) The 2-bit coding with the periodic “00”/“01”/“11”/“10” distribution. (d-f) The simulated scattering patterns of the 1-bit and 2-bit coding sequences.
Terahertz Diffusions

The coding distribution on a large area (7.56*7.56 mm$^2$), which contains 7056 coding particles constructed by the Minkowski loops.

Numerical simulation results of a 2-bit diffusion coding metasurface
The fabricated sample and measurement results. (a) Part of fabricated sample of the 2-bit diffusion coding metasurface. (b) The measured and simulated backward scattering coefficients of the 2-bit coding metasurface under the normal incidence. (c,d) The measured scattering coefficients in the specular directions of the 2-bit coding metasurface under the oblique incidences of 20 and 40 degrees, respectively. (e,f) The measured scattering coefficients in wide angles from 20 to 80 degrees of the 2-bit coding metasurface under the oblique incidences of 20 and 40 degrees, respectively.
Conformal THz Coding Metasurfaces

New Designs

Broad Band, Flexible and Conformal

Prof. Biaobing Jin
Nanjing University

Anisotropic Coding Metasurfaces

Polarization Controlled Functionalities

Anisotropic Coding Metasurfaces

More Flexible Controlled Functions …..
Cui and Liu, unpublished, 2015
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