Spatially-Variant Structures in Electromagnetics

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Presentation Outline

• Introduction
• Synthesis of spatially variant lattices
• New concepts and applications
  – Resonant grating on a curved surface
  – Spatially-variant self-collimation
  – Spatially-variant photonic crystal waveguides
  – Spatially-variant anisotropic metamaterials
• Conclusion
Design Process Using Spatial Transforms

Step 1 of 4:
Define Spatial Transform

Step 2 of 4:
Calculate Effective Material Properties

\[ \nabla \times \vec{E} = -j\omega \mu \vec{H} \]
\[ \nabla \times \vec{H} = j\omega \varepsilon \vec{E} \]
Design Process Using Spatial Transforms

Step 3 of 4:
Map Properties to Engineered Materials

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Design Process Using Spatial Transforms

Step 4 of 4:
Generate Overall Lattice

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What is a Spatially Variant Lattice?
What is a Spatially Variant Lattice?

Synthesis of Spatially-Variant Lattices
Start with Spatially-Variant Planar Gratings

Spatially-Variant Orientation
Spatially-Variant Fill Fraction
Spatially-Variant Period
Spatially-Variant Everything

Synthesis Procedure for Planar Gratings

Step 1 of 5:
Define Spatial Variance

Spatially-Variant Lattice Orientation
Spatially-Variant Lattice Spacing
Spatially-Variant Threshold
Step 2 of 5:
Calculate Spatially-Variant $K$-Function

$$\tilde{K}(\vec{r}) = \frac{2\pi}{\Lambda(\vec{r})} \left\{ \cos[\theta(\vec{r})] \hat{a} + \sin[\theta(\vec{r})] \hat{a}_r \right\}$$

Grating Vector $\tilde{K}$

Step 3 of 5:
Calculate Grating Phase

$$\nabla \Phi(\vec{r}) = \tilde{K}(\vec{r}) \quad \leftarrow \text{best fit}$$

$\cos[\tilde{K}(\vec{r}) \cdot \vec{r}]$

$\Phi(\vec{r})$
Synthesis Procedure for Planar Gratings

Step 4 of 5:
Calculate Analog SV Grating

$$\varepsilon_a(\vec{r}) = \cos[\Phi(\vec{r})]$$

Synthesis Procedure for Planar Gratings

Step 5 of 5:
Calculate Binary SV Grating

$$\varepsilon_b(\vec{r}) = \begin{cases} \varepsilon_{r_1} & \varepsilon_a(\vec{r}) < \gamma(\vec{r}) \\ \varepsilon_{r_2} & \varepsilon_a(\vec{r}) \geq \gamma(\vec{r}) \end{cases}$$
**Generalization to Arbitrary Lattices**

Unit Cell

FFT

$K_x$

$K_y$

**Arrays of Discontinuous Metallic Elements**

Spatially vary two planar gratings.
Arrays of Discontinuous Metallic Elements

Place metallic elements at the intersections.

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Arrays of Discontinuous Metallic Elements

Final device.

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Curved Metasurfaces

Spatially vary two planar gratings across a curved surface.

Curved Metasurfaces

Map surface slope to the metasurface element.
Curved Metasurfaces

Place elements at planar grating intersections.

Top View

3D View

Controlling Deformations

(a) basic algorithm
(b) 15 iterations of modified algorithm
(c) 40 iterations of modified algorithm

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Compensating for Deformations

Lattice Spacing Deviation

Lattice without any compensation.

Lattice with fill fraction compensation

Resonant Grating on a Curved Surface
**Guided-Mode Resonance**

Highly Sensitive to Angle of Incidence

Spatially Vary Grating Period to Compensate for Curvature


All-Dielectric Metasurfaces

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Spatially-Variant Photonic Crystals

Self-Collimation

- Beams do not diverge
- Beams follow the lattice
First Demonstration of Spatially-Variant Self-Collimation

- Manufactured by 3D printing
- Operated at 15 GHz


Spatially-Variant Self-Collimation for Photonics

- World’s tightest unguided bend ($R = 6.7\lambda_0$).
- Utilized very low refractive index (SU-8, $n \approx 1.59$).
- Operated at $\lambda_0 = 2.94 \, \mu m$.

Spatially-Variant Anisotropic Metamaterials


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All-Dielectric Anisotropic Metamaterials

- All-dielectric
- Very low loss
- Ultra broadband
- Positive uniaxial


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Microstrip Made Immune to Metal Object in Close Proximity


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Conclusion

- SV tool is a necessary step for spatial transforms.
- SV tool enables new device concepts and applications.
  - Resonant grating on curved surfaces
  - Spatially-variant self-collimation
  - Spatially-variant photonic crystal waveguides
  - Spatially-variant anisotropic metamaterials

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