Lecture #20

Frequency Selective Surfaces and Metasurfaces

Lecture Outline

• Introduction
• Simple examples
• Grating lobes
• Classifications and comparisons
• All-dielectric frequency selective surfaces
• Metasurfaces
• Conclusions
Introduction

Definition of Frequency Selective Surface

A frequency selective surface is typically a “flat” composite material designed to be transparent in some frequency bands while reflective, absorbing or redirecting to others. They are typically flat and composed of metal screen.
Examples

The First Radio Frequency FSS
Physical Mechanisms for Frequency Selectivity

**FREQUENCY SELECTIVE SURFACE**
To perform frequency selectivity (filtering), energy must be absorbed and/or redirected.

**ABSORPTION**
Devices are made absorptive by incorporating lossy materials. The absorption can be amplified by also incorporating resonant structures.

**REDIRECTION**
Energy is redirected using interference and diffraction. This can be simple reflection, diffraction from a grating or through a guided-mode resonance.

---

Some Simple Examples
Salisbury Screen

A Salisbury screen was one of the first concepts for frequency selective surfaces and was used by the military to make military vehicles “invisible” to radar.

At the frequency in which the device is resonant, energy is absorbed in the lossy material.

Circuit Analog Absorber

A circuit analog absorber is like a Salisbury screen, but it incorporates periodic structures that amplify the absorption by enhancing the resonance.

Can provide sharper or more tailored resonances
“Perfect” Metamaterial Absorbers


Grating Lobes
Definition of Grating Lobes

Frequency selective surfaces are diffraction gratings and will diffract an applied wave into discrete directions if the frequency is high enough.

This is usually seen as a bad thing.

RF engineers call these grating lobes or specular reflection. Optical engineers call these diffraction orders. They are “lobes” due to the bandwidth of the signal.

Grating lobes are a far-field concept. It does not make sense to think about grating lobes within a device.

Grating Lobe Condition

Grating Lobe Condition (Grating Equation)

\[ k_i n \sin \theta_m = k_i n_{inc} \sin \theta_{inc} - \frac{2 \pi m}{\Lambda_s} \]

\[ n \sin \theta_m = n_{inc} \sin \theta_{inc} - m \frac{2 \pi}{\Lambda_s} \]

\( k_i \) = refractive index around diffracted order
\( n_{inc} \) = refractive index around applied wave
\( \Lambda_s \) = interelement spacing (grating period)
\( m = \ldots, -2, -1, 0, 1, 2, \ldots \)
Onset of Grating Lobes

Although grating lobes can provide a redirection mechanism for frequency selectivity, they are typically viewed as a bad thing.

It is usually desired to operate FSSs at frequencies below a cutoff where there are no grating lobes (no diffracted modes).

Assuming the FSS is operated in air ($n=n_{inc}=1.0$), this cutoff condition (onset of grating lobes) occurs when $\theta_{\pm1}=90^\circ$:

$$f_c = \frac{c_0}{\Lambda_s (\sin \theta_{inc} - 1)}$$

$$\lambda_{0,c} = \Lambda_s (\sin \theta_{inc} - 1)$$

Classifications and Comparisons
Redirection Mechanisms

**Longitudinal Resonance**

A beam is incident from the top and partially reflects from each of the surfaces. It is the overall interference of the scattered waves that produces the frequency selectivity.

**Transverse Resonance**

An external wave is coupled into a guided mode or surface wave. The guided-mode slowly leaks from the guide due to the grating. It is the interference between the applied wave and the “leaked” wave that produces the frequency selectivity.

**Diffractive**

An applied wave is incident on a grating that scatters it into multiple directions. Frequency selectivity is produced by the inherent frequency dependence of scattering from a grating.

Multilayer Vs. Single Layer FSS

A tremendous amount of control over the shape of the response of a FSS can be realized using multilayer resonant structures. This approach can combine absorption, longitudinal resonance, transverse resonance and diffraction into a single device.

Multilayer structures are generally more sensitive to angle of incidence.

*FIGURE 1.7. By using cascaded periodic structures we can obtain a broader top and faster roll-off. However, the bandwidth will vary considerably with angle of incidence.*
The above structures are also called “complementary” arrays because they are exact inverses of each other. According to Babinet’s principle for complementary surfaces, their frequency responses will also be exact inverses of each other. In practice, this is not the case because the metals are not perfectly conducting and not infinitely thin. Further, if dielectric is incorporated, these structures can behave very differently.

Array Symmetry Considerations

Frequency selective surfaces are essentially planar devices so we need only consider the five 2D Bravais lattices.

For a given element shape, the hexagonal array can fit more elements per unit area than any other symmetry. Hexagonal arrays have higher “packing density.”

Equivalently, the element size can be larger relative to the lattice spacing in a hexagonal array.

The onset of grating lobes tends to be farther out for hexagonal arrays so they are most desirable from this perspective.

Modeling and manufacturing hexagonal arrays can be more difficult.

Fill Fraction Comparison

\[ f = \frac{2L}{a} \]

\[ f = \pi \left( \frac{r}{a} \right)^2 \]

\[ f = \frac{2\pi}{\sqrt{3}} \left( \frac{r}{a} \right)^2 \]

Hexagonal array provides 15.4% higher fill fraction
Common Element Types

- $L = \frac{\lambda}{2}$
  - LP polarizer
  - Can be pushed tight, broadband
  - Very broadband
  - Large relative to wavelength
  - Angle sensitive
  - Grating lobes a problem
  - Larger elements relative to wavelength
  - Secondary resonances problematic

- $c = \lambda_0$
  - Group 2: "Loop Types"
  - Small relative to wavelength
  - Circumference is $\lambda_0$
  - Common band pass element
  - BW control through line thickness

- $L = \frac{\lambda}{2}$
  - Group 3: "Solid Interior" or "Plate Type"
  - Earliest and simplest elements studied
  - Large relative to wavelength
  - Angle sensitive
  - Grating lobes a problem

All-Dielectric Frequency Selective Surfaces
Why All-Dielectric?

- Metals can be lossy (especially at optical frequencies)
- Structure may need to be low observable (LO)
- Can be handled more safely in high-voltage environments
- Maybe better suited for high power
- Can be monolithic

Dielectric Mechanisms for Frequency Selectivity

- Stacks of layers
  - Great for optics, but bulky at radio and microwave frequencies
- Naturally absorbing materials
  - May be best approach if it is possible
- Diffraction gratings
- Guided-mode resonance
  - Limited bandwidth
  - Limited field-of-view
  - Typically required to be 100’s of periods
**All-Dielectric FSS with Few Periods**


**All-Dielectric FSS on Curved Surface**

Metasurfaces are essentially planar nonresonant metamaterials.

Ingredients for a definition:

- Subwavelength thickness
- Flat composite structure
- Engineered electromagnetic properties
- Affects waves through modified boundary conditions instead of effective properties

http://www.innoget.com/O.3072/Method-for-designing-a-modulable-metasurface-antenna-structure
**Metasurfaces Vs. Metamaterials**

**Metamaterials** – function is to realize artificial $\mu$ and $\varepsilon$.

Metamaterials – function is to realize artificial $\mu$ and $\varepsilon$.

**Metasurfaces** – function is to modify wave fronts arbitrarily.

Metasurfaces – function is to modify wave fronts arbitrarily.

Metasurfaces can arbitrarily control the following as a function of position:
- Amplitude
- Polarization
- Phase
- Angles (i.e. phase)
- Frequency (nonlinear)
- Reciprocity (nonlinear, anisotropic, etc.)

**Standard Law of Reflection**

The standard law of reflection states that the angle of incidence ($\theta_{\text{inc}}$) is equal to the angle of reflection ($\theta_{\text{ref}}$).

$$\theta_{\text{ref}} = \theta_{\text{inc}}$$
How Does Phase Accumulate Across Surface?

\[
\phi_{\text{inc}}(x) = k_{x,\text{inc}}x \quad \quad \phi_{\text{ref}}(x) = k_{x,\text{ref}}x
\]

\[
\frac{d\phi_{\text{inc}}}{dx} = k_{x,\text{inc}} \quad \quad \frac{d\phi_{\text{ref}}}{dx} = k_{x,\text{ref}}
\]

What If the Surface Affected Phase?

\[
\phi_{\text{inc}}(x) = k_{x,\text{inc}}x \quad \quad \phi_{\text{ref}}(x) = k_{x,\text{ref}}x - \frac{\Phi_{\text{ms}}}{k_0}
\]

\[
\frac{d\phi_{\text{inc}}}{dx} = k_{x,\text{inc}} \quad \quad \frac{d\phi_{\text{ref}}}{dx} = k_{x,\text{ref}} - \frac{1}{k_0} \frac{d\Phi_{\text{ms}}}{dx}
\]

Uh oh! \( \theta_{\text{ref}} \neq \theta_{\text{inc}} \)
**Modified Law of Reflection**

\[
k_{\text{x,inc}} = k_{\text{x,ref}} - \frac{1}{k_0} \frac{d\Phi_{\text{ms}}}{dx}
\]

\[
n_1 \sin \theta_{\text{inc}} = n_2 \sin \theta_{\text{ref}} - \frac{1}{k_0} \frac{d\Phi_{\text{ms}}}{dx}
\]

**Modified Law of Refraction**

\[
k_{\text{x,inc}} = k_{\text{x,tm}} - \frac{1}{k_0} \frac{d\Phi_{\text{ms}}}{dx}
\]

\[
n_1 \sin \theta_{\text{inc}} = n_2 \sin \theta_{\text{tm}} - \frac{1}{k_0} \frac{d\Phi_{\text{ms}}}{dx}
\]
Conclusions about FSSs

• Typically want small and tightly packed elements
  – Broadband
  – Robust to angle of incidence
  – Grating lobes less problematic
• The resonant frequency and bandwidth usually depends mostly on the element shape and size, not the array spacing or symmetry.
• The frequency where grating lobes are present depends only on the element spacing and angle of incidence, not the element type (remember FSSs are gratings)
• All-dielectric FSS are an option for niche applications.
Conclusions About Metasurfaces

- Elements are much more subwavelength than with FSSs
- Elements control wave fronts
  - Amplitude
  - Polarization
  - Phase
  - Angles
  - Frequency
  - Reciprocity