PHOTONIC BAND GAPS IN THREE DIMENSIONS:
NEW LAYER-BY-LAYER PERIODIC STRUCTURES

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A new three-dimensional (3D) periodic dielectric structure constructed with layers of dielectric rods of circular, elliptical, or rectangular shape is introduced. This new structure possesses a full photonic band gap of appreciable frequency width. At midgap, an attenuation of 21 dB per unit cell is obtained. This gap remains open for refractive indices $n > 1.9$. Furthermore, this new 3D layer structure potentially has the additional advantage that it can be easily fabricated using conventional microfabrication techniques on the scale of optical wavelengths.
Happy Birthday Costas!

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Transport Properties of One-way EM waveguide formed at the interface between metal and 2D photonic crystal

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Outline

• Motivation
• Nonreciprocity – necessary conditions, role of the time-reverse symmetry breaking in nanodevices
• Nonreciprocal and one-way devices – concepts
• Spectral and transport properties of one-way waveguide
• Dependence of unidirectional behaviour on boundary conditions and when mg. field is modulated
• Discussion and conclusions
Motivation

• To explore physical mechanisms that may lead to nonreciprocal devices

• Provide hints to design compact integrated optical analog to one-way electronic device such is diode or transistor to contribute to the effort to make photonics more realistic alternative to electronic solutions
Nonreciprocity in the context of the nanodevices

Effects of the disorder are significantly influenced time-reverse symmetry properties.

Reciprocal systems:
- the backreflection in the presence of disorder may constitute serious drawback

Non-reciprocal systems with broken TR symmetry:
- a new regime of photon transport that supports only forward propagating wave that is free of disorder-induced backscattering
Nonreciprocity $\omega(k) \neq \omega(-k)$

To satisfy a sufficient condition to ensure spectral non-reciprocity $\omega(-k) \neq \omega(k)$ requires breaking both space- and time-reversal symmetry [1]

A generic 1D periodic arrangement of magnetic and dielectric components that give rise to strong spectral asymmetry [2] has been suggested

Nonreciprocal devices - concepts

Design proposed in Ref. 3 employs photonic analogues of quantum chiral edge states and relies on the presence of a degenerate Dirac point in reciprocal photonic crystal.

Various designs of one-way waveguides operating at microwave range proposed in Ref. [4]-[7].

One-way EM waveguide


Waveguide A

Dielectric permittivity of the metal:

\[ \tilde{\varepsilon}(\omega) = \varepsilon_1 - \frac{\omega_p^2}{(\omega + i\gamma)^2 - \omega_b^2} \cdot \begin{pmatrix} 0 & \frac{i\omega_b}{\omega} & 0 \\ \frac{i\omega_b}{\omega} & 1 + i\frac{\gamma}{\omega} & 0 \\ 0 & 0 & \frac{(\omega + i\gamma)^2 - \omega_b^2}{\omega(\omega + i\gamma)} \end{pmatrix} \]

\( \varepsilon_1 = 1 \)
\( \varepsilon_{\text{dielectric}} = 8.9 \)

\( \gamma = 1.10^{14} \text{ rad/s} \)
\( \omega_p = 1.10^{16} \text{ rad/s} \)

\( a = 100 \text{ nm} \)
\( d = 0.2a \)
\( a = 50 \text{ nm} \)
Waveguide A

\[ \omega_{SPL} = \omega_{SP} - \frac{\omega_B}{2} \]

\[ \omega_{SPR} = \omega_{SP} + \frac{\omega_B}{2} \]

\[ \omega_B = \frac{eB}{m} \]

\[ \omega_{SP} = \frac{\omega_p}{\sqrt{2}} \]
One-way waveguide concepts vs. Bloch theorem

In order to achieve true one-way property it is crucial that within a certain frequency range there appears a photonic band that has a single sign for its group velocity over the whole Brillouin zone.

\[ \omega(\pi/a) = \omega(-\pi/a) \]
Artificial periodization of the waveguide structure to be modeled (with propagation along z). The dashed regions are the PML absorbers isolating the “grating unit cells”. By a proper Fourier factorization in the $x$-direction the local eigenmode basis can be described by discrete plane wave expansion.

$$\begin{pmatrix} F_{out} \\ B_{in} \end{pmatrix} = \begin{pmatrix} \overline{T}_{in, out} & \overline{R}_{out, in} \\ \overline{R}_{in, out} & \overline{T}_{out, in} \end{pmatrix} \begin{pmatrix} F_{in} \\ B_{out} \end{pmatrix}$$

$$\begin{pmatrix} \overline{T}_{in, out} & \overline{R}_{out, in} \\ 0 & \overline{T}_{out, in} \end{pmatrix} \begin{pmatrix} F_{in} \\ e^{jk_{\parallel}a}B_{in} \end{pmatrix} = e^{-jk_{\parallel}a} \begin{pmatrix} \overline{I} & 0 \\ \overline{R}_{in, out} & \overline{T}_{out, in} \end{pmatrix} \begin{pmatrix} F_{in} \\ e^{jk_{\parallel}a}B_{in} \end{pmatrix}$$

Generalized eigenvalue problem with applying Bloch boundary conditions which allows to calculate band structures in the frequency domain with frequency as the independent parameter.
The field plots show the z-component of the Poynting vectors at the reduced frequency $0.7\omega_p$ inside one unit cell of the structure shown on the left. Lighter shades indicate positive $S_z$. In the obtained dispersion diagram a forward and a backward plasmonic mode are found at this frequency. The field plots show that $+z$ and $-z$ propagating plasmonic modes are guided at opposite metallic interfaces.
qualitative demonstration of the possibility to obtain similar unidirectional regime by using a magnetic PhC and a nonmagnetic metal with one way frequency range $0.366 < \omega/\omega_p < 0.376$

$\sim 363 \text{ nm} < \lambda < 373 \text{ nm}$
Theoretical model

Surface plasmon polaritons propagating along the interface between two semi-infinite homogenous slabs fabricated from BIG and Ag

\[ \tilde{\varepsilon} = \begin{pmatrix} \varepsilon & i g & 0 \\ -i g & \varepsilon & 0 \\ 0 & 0 & \varepsilon \end{pmatrix} \]

\[ \varepsilon(\omega) = 1 + \frac{\omega_p^2}{\omega^2} \]

\[ \varepsilon_{xx} = \varepsilon_{yy} = \varepsilon_{zz} = \varepsilon = 6.25, \quad g = 0.1 \]

\[ \omega_p = 1.381 \times 10^{16} \text{ rad/s} \]

\[ \gamma = 6.28 \times 10^{12} \text{ rad/s} \]

Dispersion relation

Surface plasmon polaritons propagating along the interface between two semi-infinite homogenous slabs fabricated from BIG and Ag

\[
k_x^2 = k_0^2 \frac{K_1 \pm K_2}{(\varepsilon_m^2 - \varepsilon_v \varepsilon_{xx})^2 + 4\varepsilon_m^2 \varepsilon_{xy}^2}
\]

\[
K_1 = (\varepsilon_v \varepsilon_{xx} - \varepsilon_m^2)(\varepsilon_v - \varepsilon_m)\varepsilon_m \varepsilon_{xx} + 4\varepsilon_m^3 \varepsilon_{xy}^2
\]

\[
K_2 = 2i \varepsilon_{xy} \varepsilon_m^2 \sqrt{\varepsilon_m \varepsilon_{xx}(2-(\varepsilon_m^2 + \varepsilon_v \varepsilon_{xx}))}
\]

\[
\varepsilon_v = \varepsilon_{xx} + \frac{\varepsilon_{xy}^2}{\varepsilon_{xx}}
\]

\[
\varepsilon(\omega) = 1 + \frac{\omega_p^2}{\omega^2}
\]

Dispersion relation

Surface plasmon polaritons propagating along the interface between two semi-infinite homogenous slabs fabricated from BIG and Ag

\[ \frac{1}{\sqrt{\varepsilon + 1}} \]

\[ \frac{\omega}{\omega_p} \]

\[ k_y/k_p \]

Effect of Boundary Case conditions Case I

One-way propagation in the waveguide structure formed the interface between metal and a MOPhC @ frequency $\omega_c = \omega_p/\sqrt{7.25}$ inside the band gap: PML boundary conditions
Effect of Boundary Case conditions Case II

\[ \omega_c = \frac{\omega_p}{\sqrt{7.25}} \] inside the band gap: Perfect conductor (PC) boundary conditions
Effect of Boundary Case conditions Case III

\[ \omega_c = \omega_p / \sqrt{7.25} \] inside the band gap: PC wall placed into middle of PhC unit cell C
Conclusions

• Improved one-way waveguide that assumes significantly reduced mg. field $\sim 0.01 \, T$

• Spectral and transport characteristics have been studied

• Dependence on boundary conditions and temporal modulation of the mg. field

• Some new and interesting phenomena observed
Conclusions

Future directions:

two major challenges to be addressed

1. reduce or completely avoid using mg. field,

2. scale operating wavelength to optical range

Χαρούμενα Γενεθλία Costas!