

# RAZVOJ IN PRIHODNOST NANOFOTONSKIH INTEGRIRANIH VEZIJ

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# Laboratorij za Fotovoltaiško in Optoelektroniko

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## Vodja

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## Raziskovalci

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izr. prof. dr. Janez Krč  
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dr. Kristijan Brecl  
dr. Urša Opara Krašovec  
dr. Boštjan Glažar  
dr. Andrej Čampa  
dr. Marko Berginc  
dr. Mateja Hočevnar  
dr. Benjamin Lipovšek

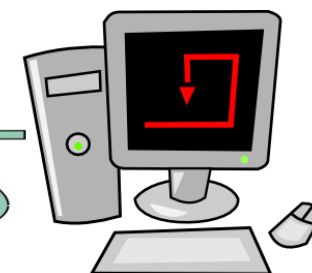
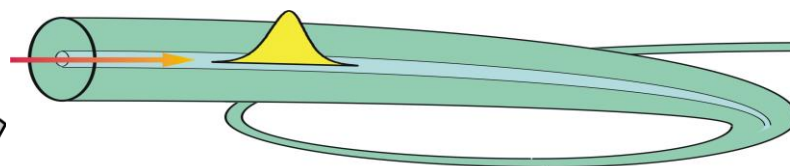
## Mladi raziskovalci

Matevž Bokalič  
Marija Drev  
Miha Filipič  
Blaž Kirn  
Gašper Matič  
Martin Sever  
Tjaša Vidmar

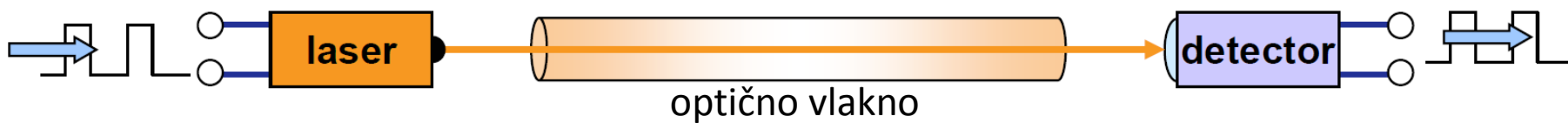
## Tehnična sodelavca

Jože Stepan  
Marijan Žurga

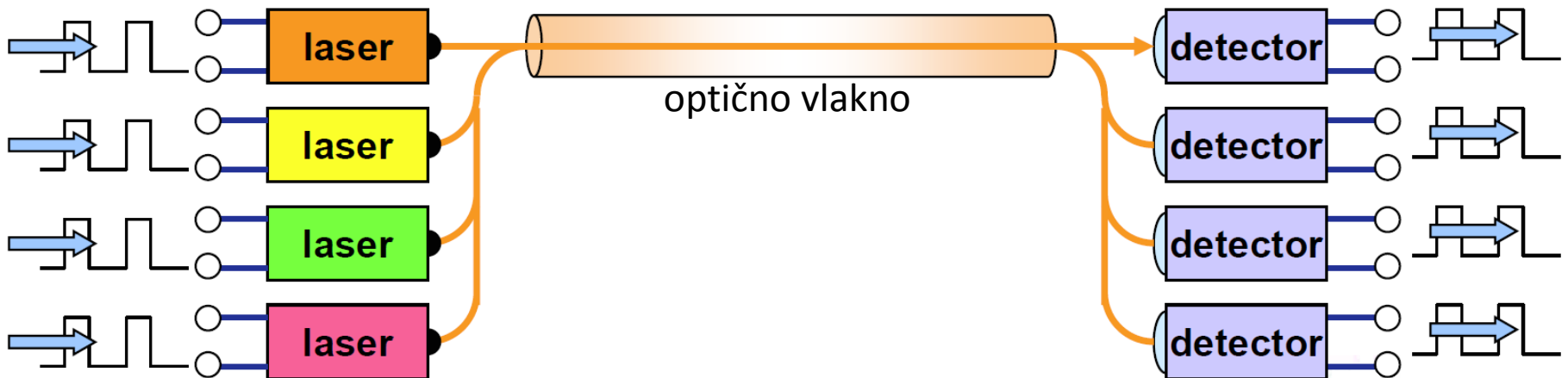
# Telekomunikacije



# Optične telekomunikacije

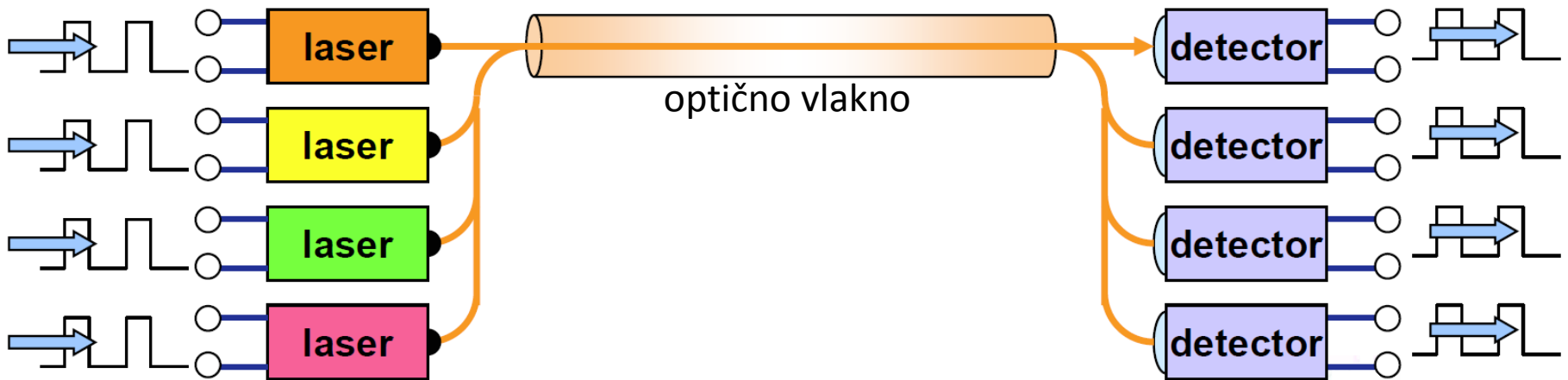


# Optične telekomunikacije



vir: IMEC

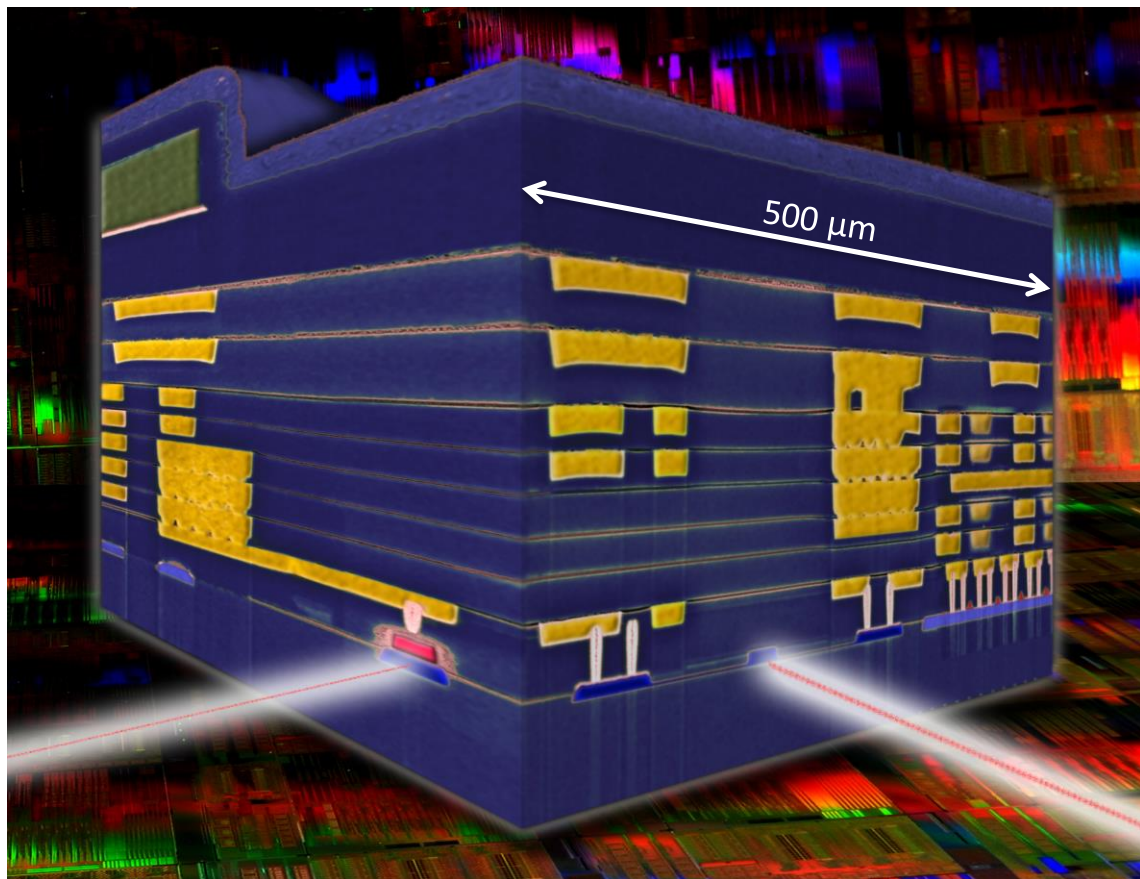
# Optične telekomunikacije



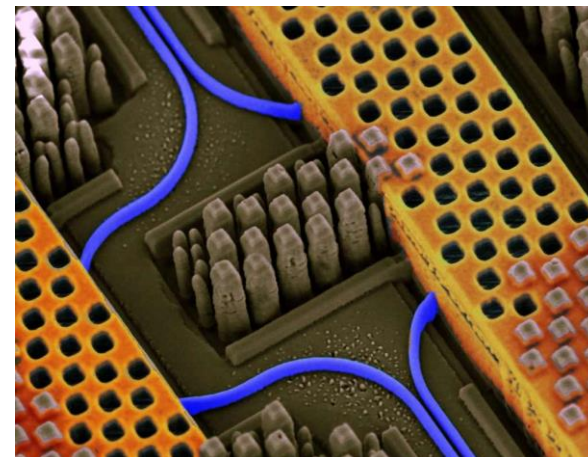
vir: IMEC

- › Integracija na nivoju čipa?
- › Optična komunikacija med mikroprocesorji?
- › Optična komunikacija med mikroprocesorjem in polnilnikom?

# Fotonska integrirana vezja (IBM, 2012)

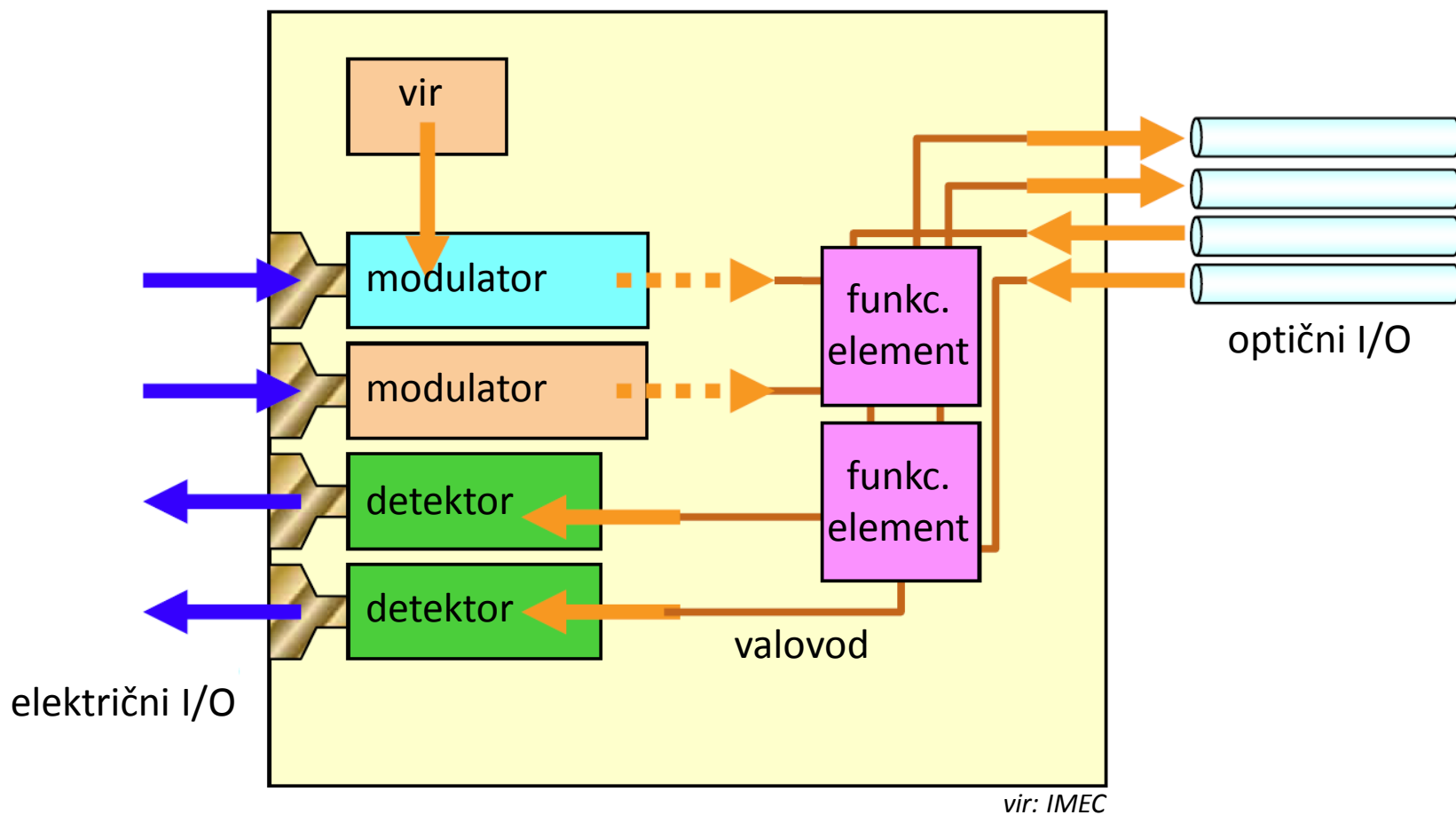


vir: IBM



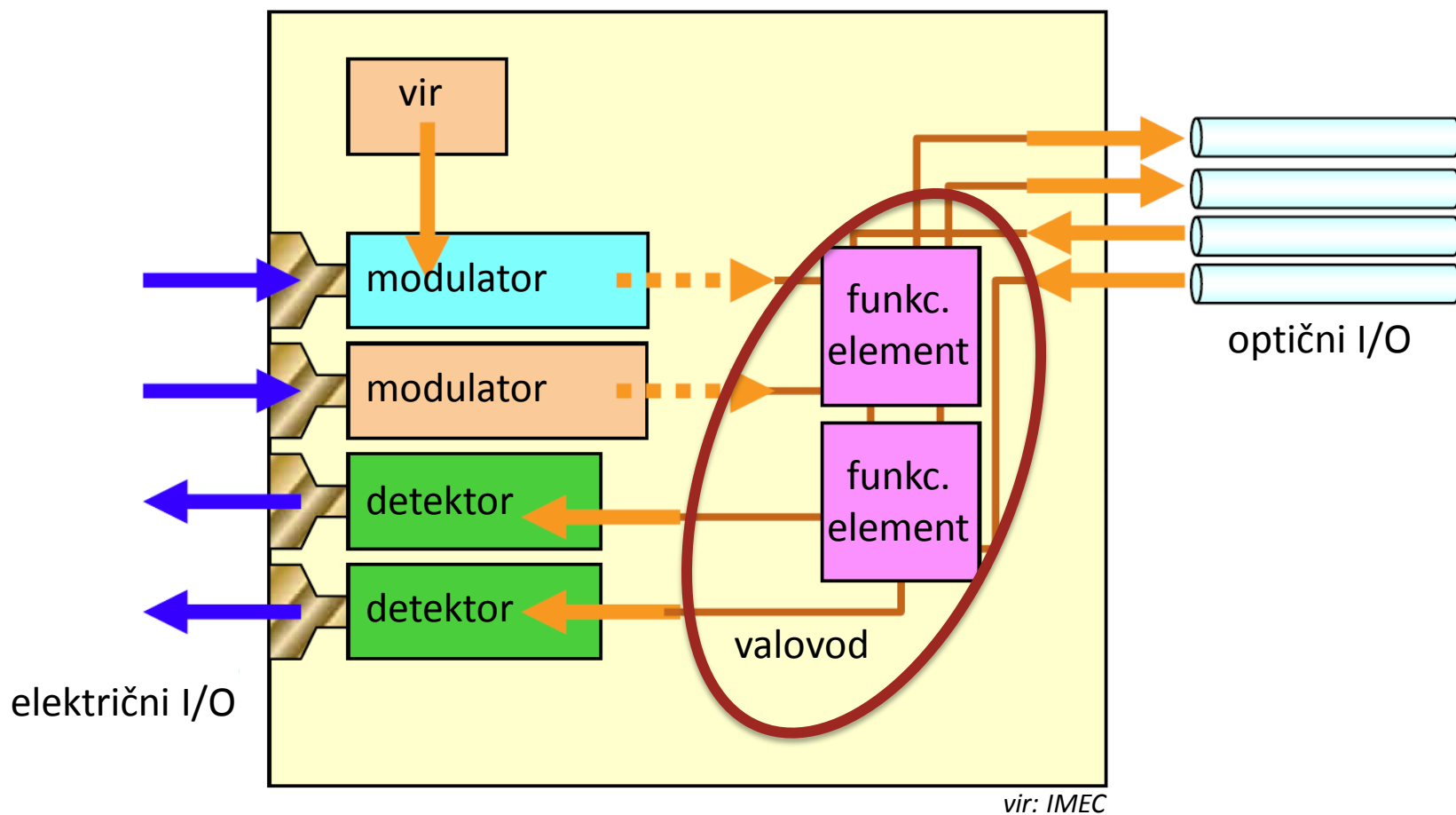
- › 90 nm CMOS tehnologija
- › Integracija elektronskih in fotonskih elementov
- › Hitrost 25 Gb/s na kanal
- › Nizka cena!

# Fotonska integrirana vezja

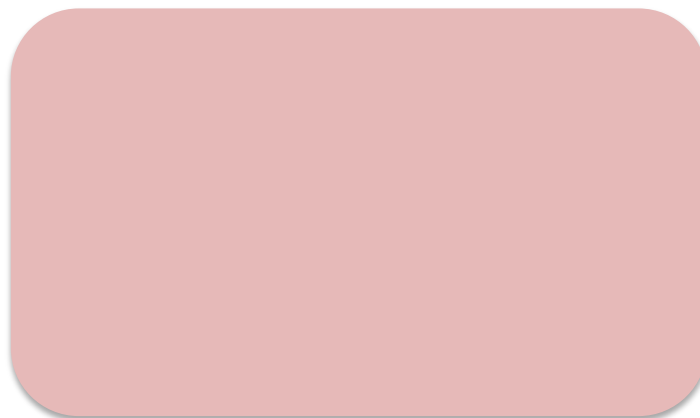




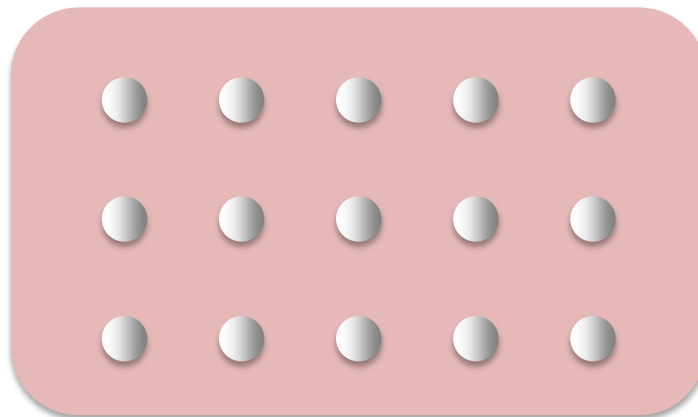
# Fotonska integrirana vezja



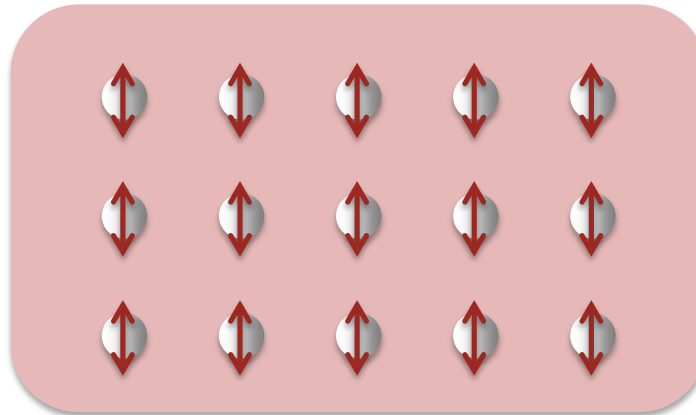
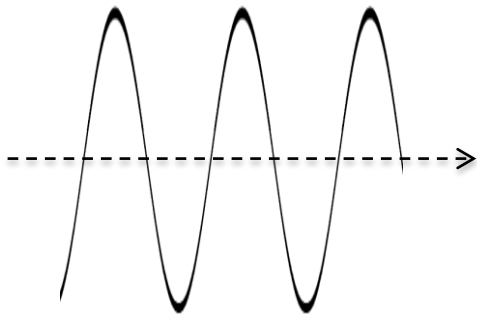
# Svetloba in snov



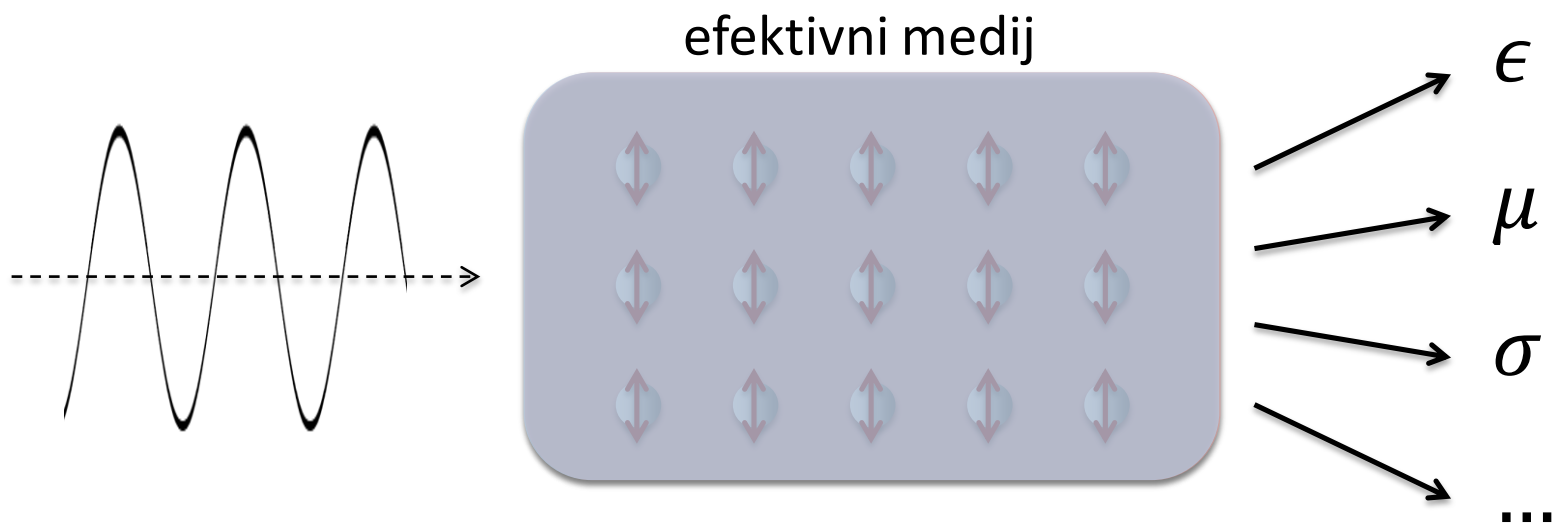
# Svetloba in snov

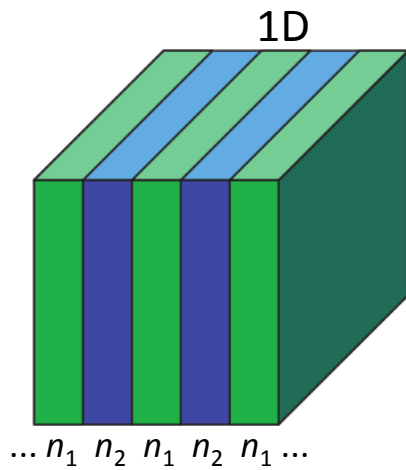


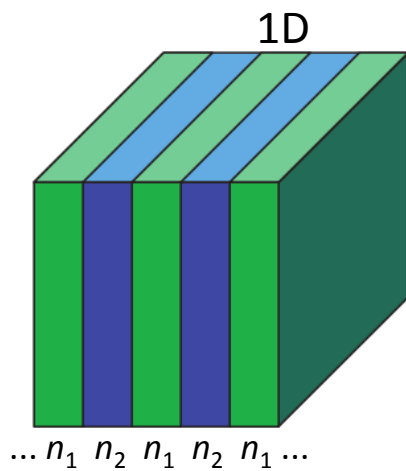
# Svetloba in snov



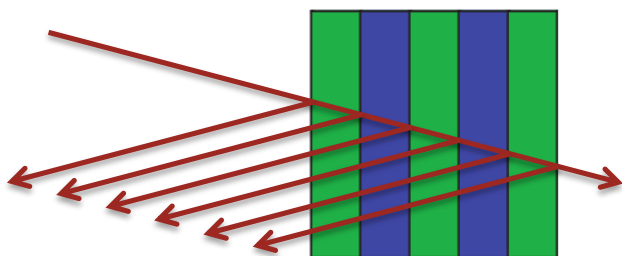
# Svetloba in snov

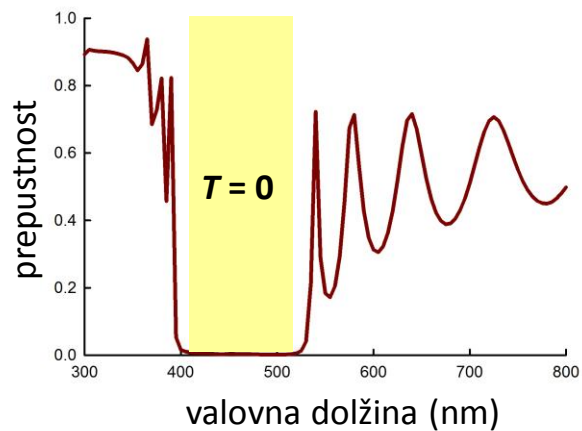
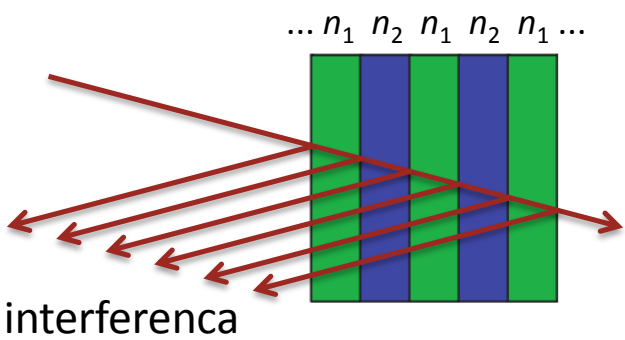
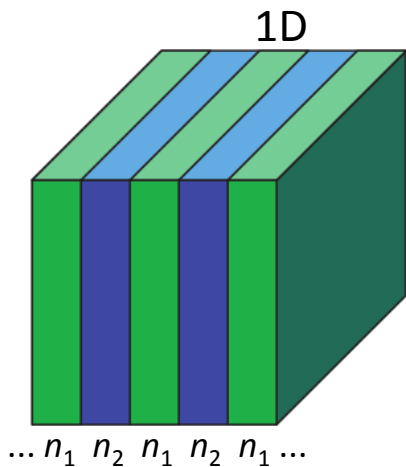




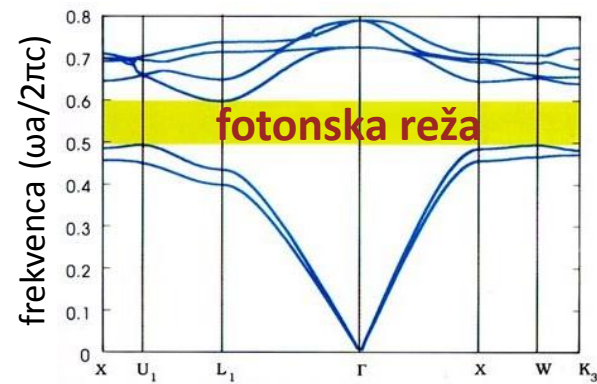
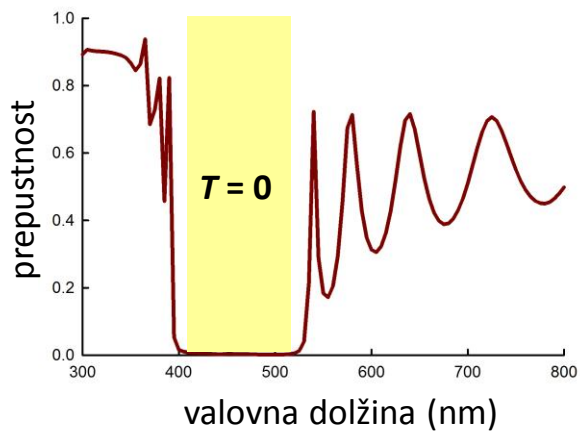
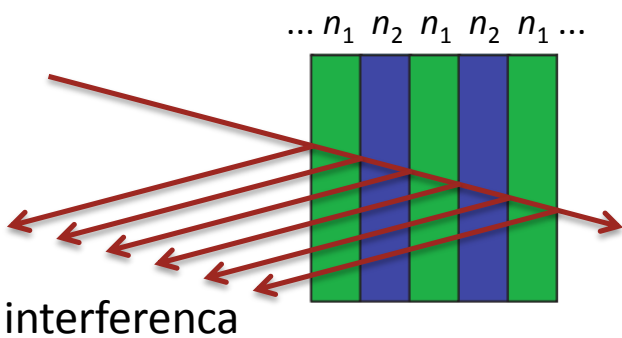
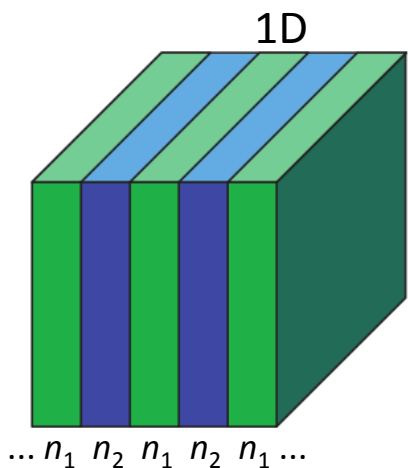


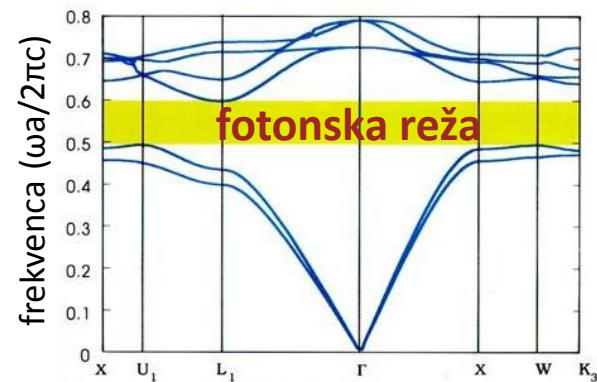
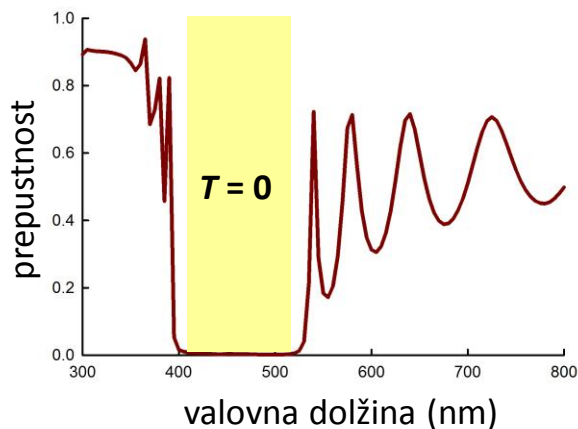
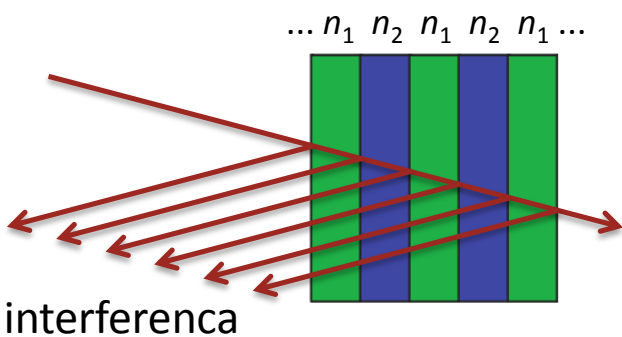
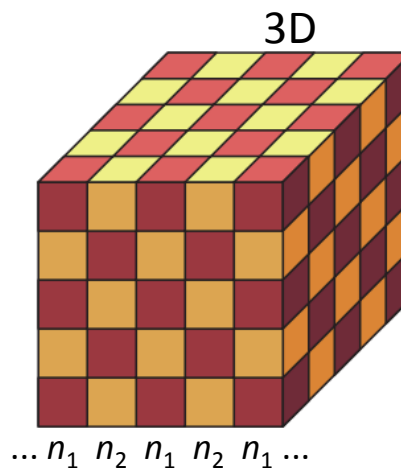
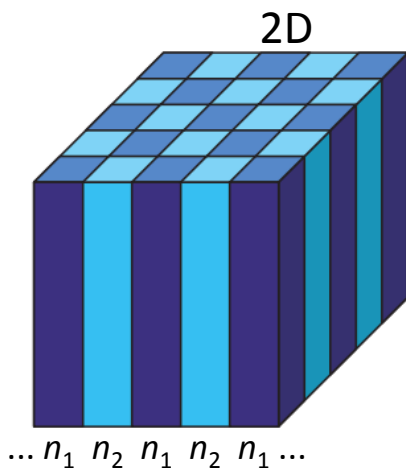
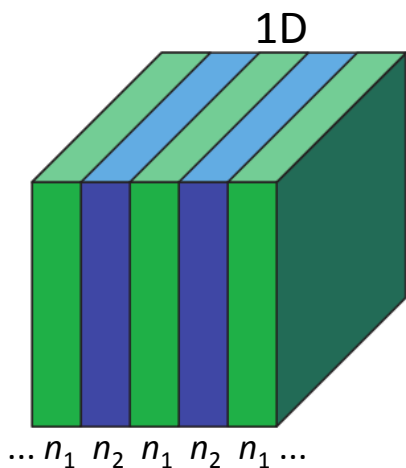
...  $n_1$   $n_2$   $n_1$   $n_2$   $n_1$  ...



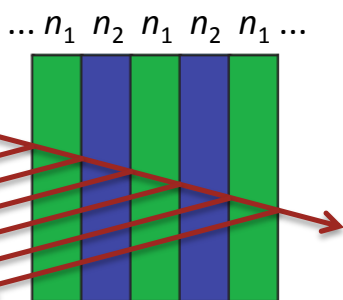
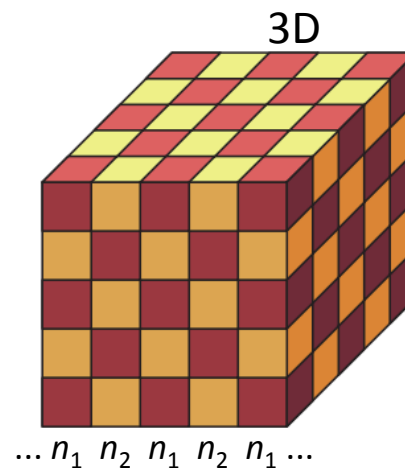
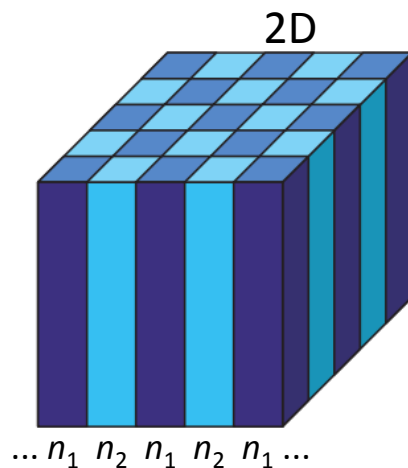
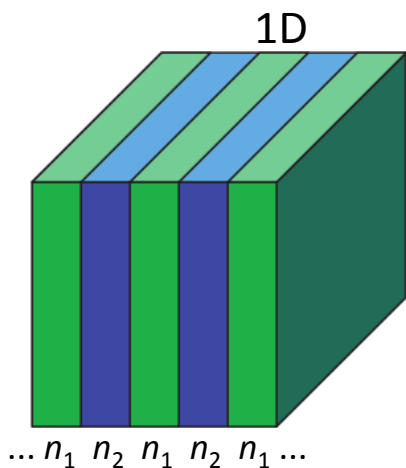




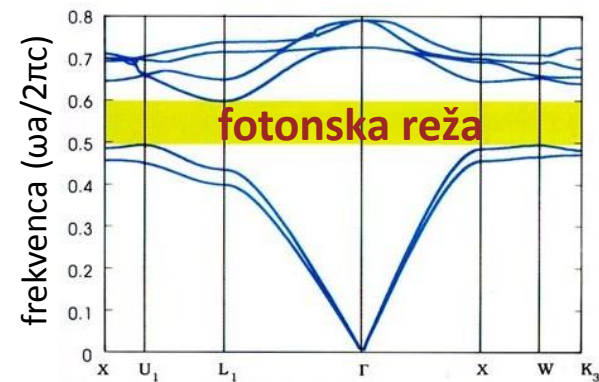
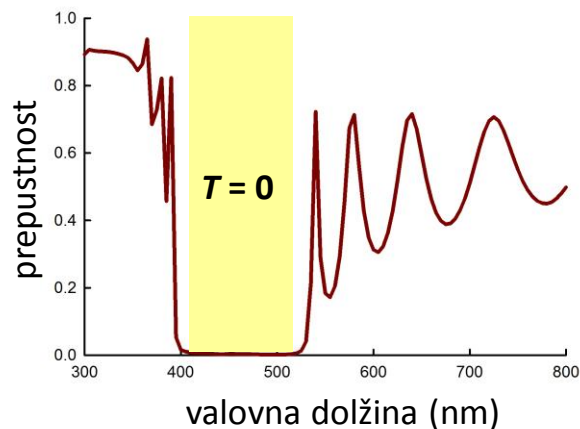




# Fotonski kristali (PC)



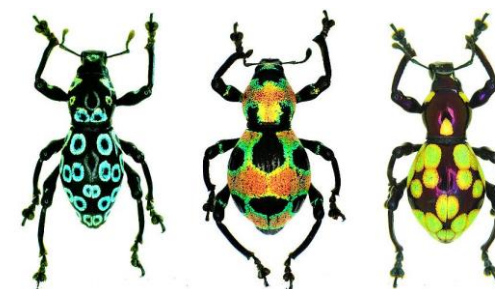
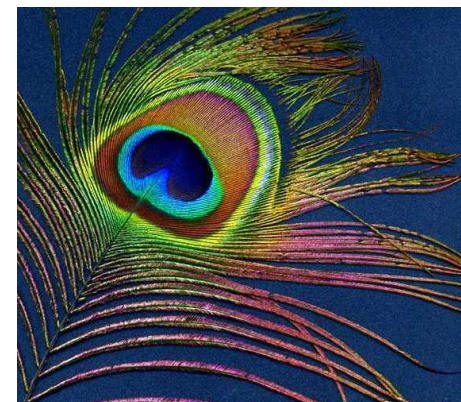
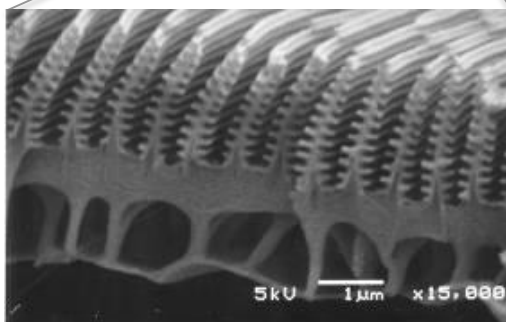
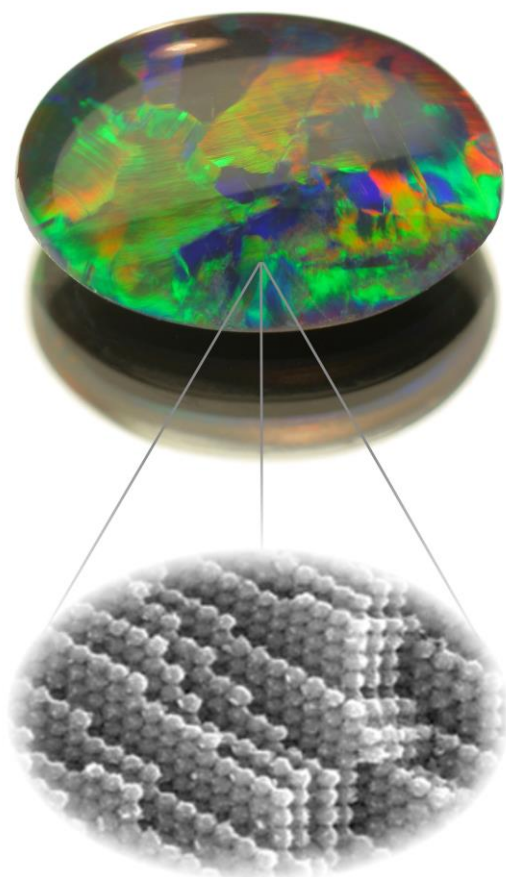
interferenca



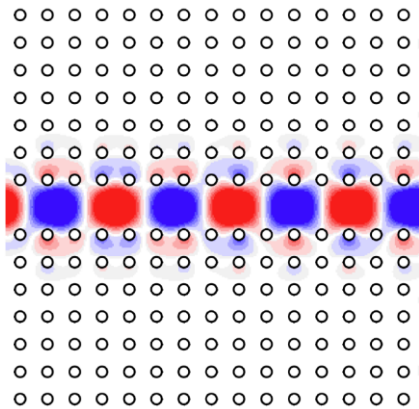
# Fotonski kristali – nov koncept?



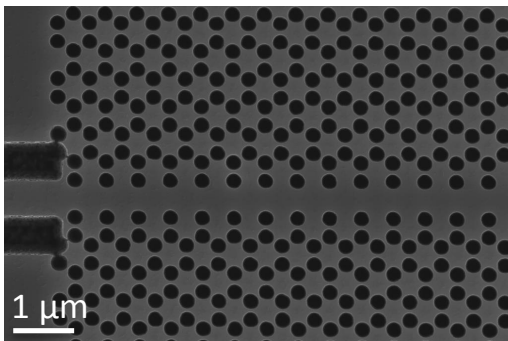
# Fotonski kristali – nov koncept?



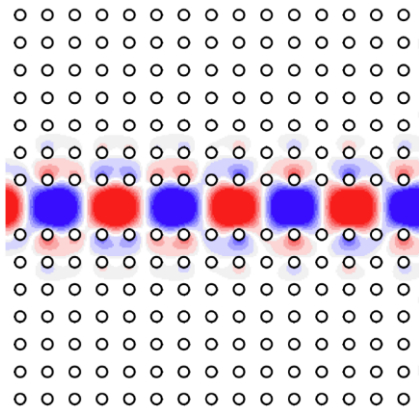
# Fotonsko kristalni valovodi (svetlovodi)



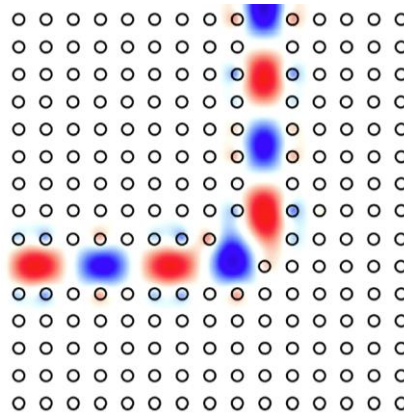
a) valovod



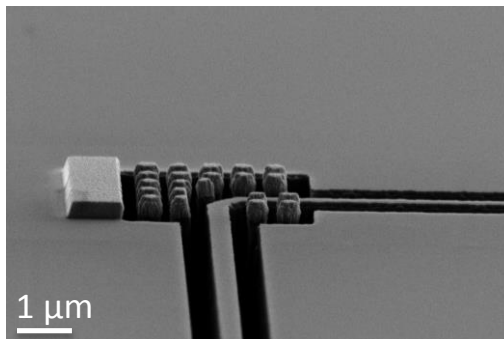
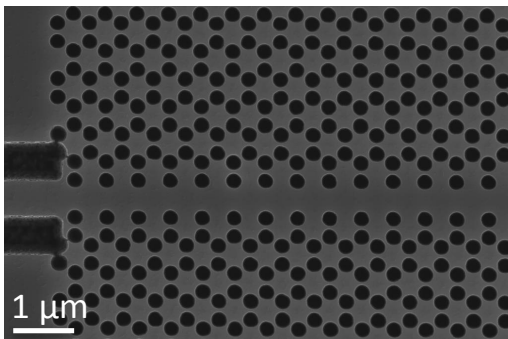
# Fotonsko kristalni valovodi (svetlovodi)



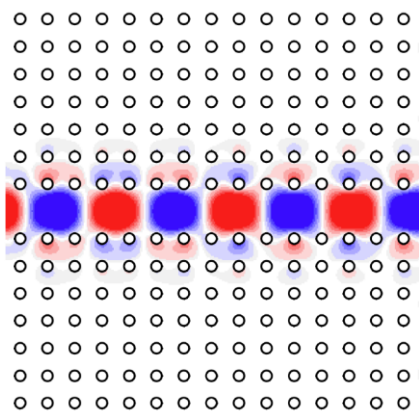
a) valovod



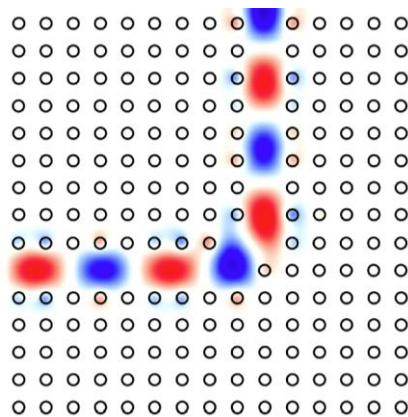
b) idealni 90° zavojev



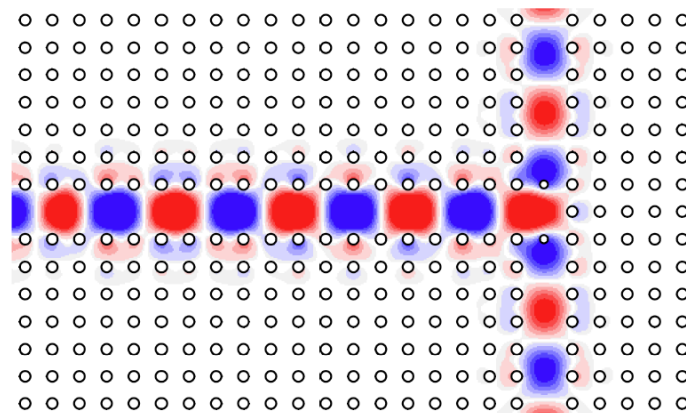
# Fotonsko kristalni valovodi (svetlovodi)



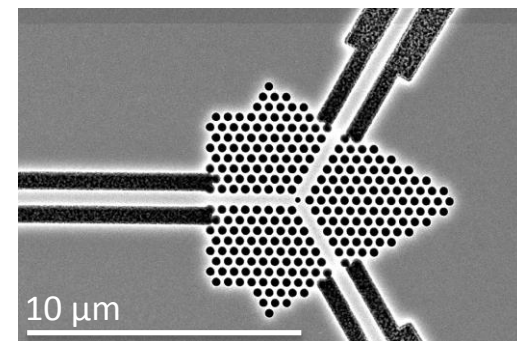
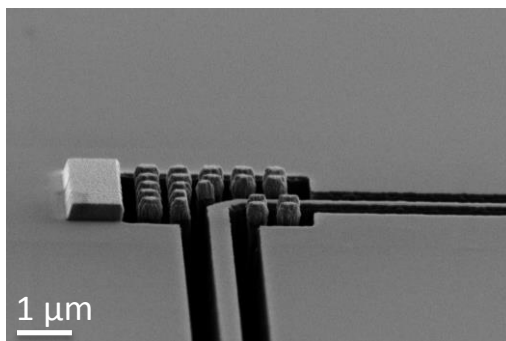
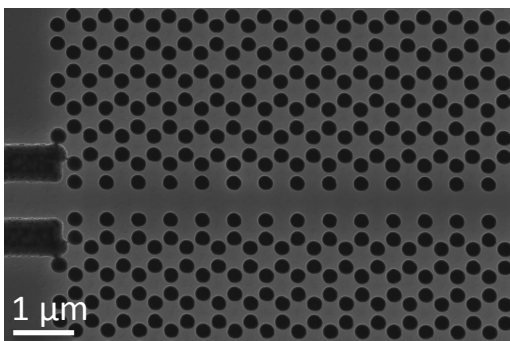
a) valovod



b) idealni 90° zavoje



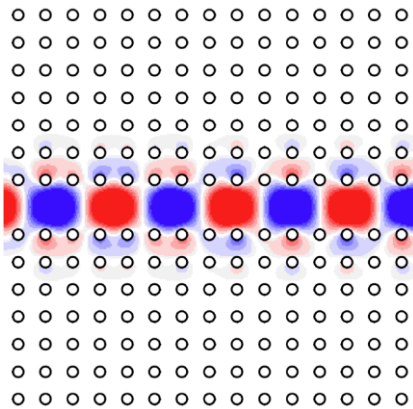
c) delilnik žarka



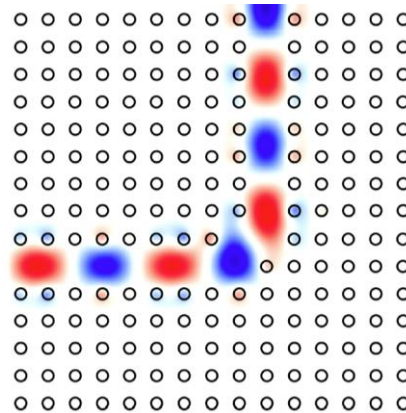
vir: ETH, Zürich



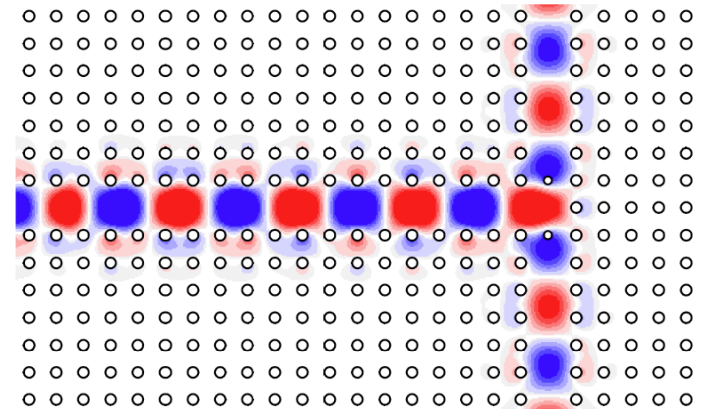
# Fotonsko kristalni valovodi (svetlovodi)



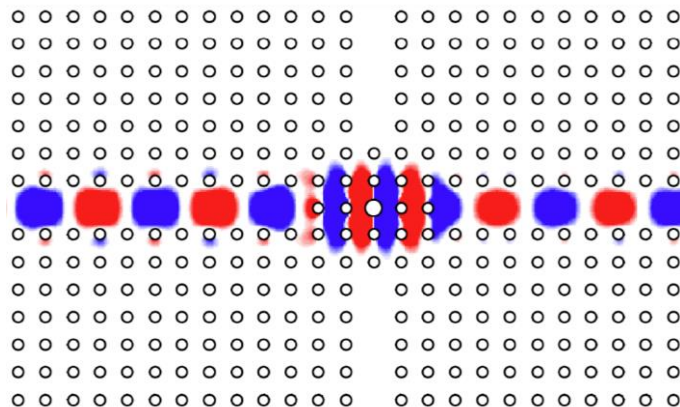
a) valovod



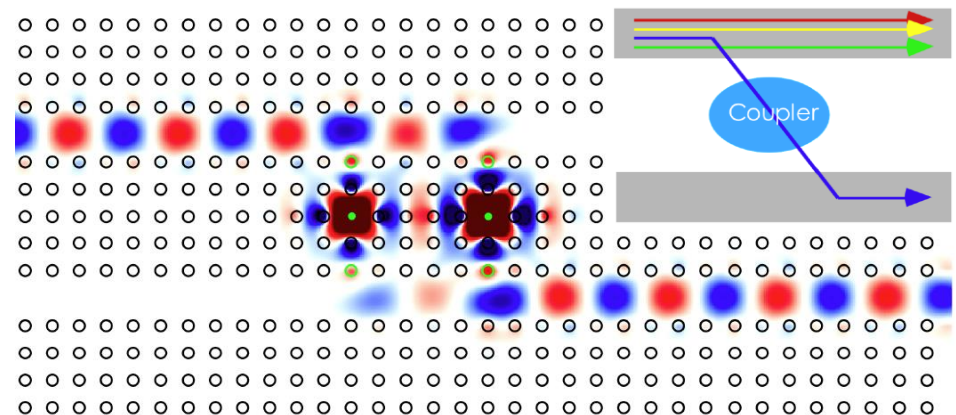
b) idealni 90° zavoj



c) delilnik žarka



d) križanje valovodov brez motenj



e) filtriranje komponent („channel drop filter“)

# Fotonsko kristalna optična vlakna (PCF)

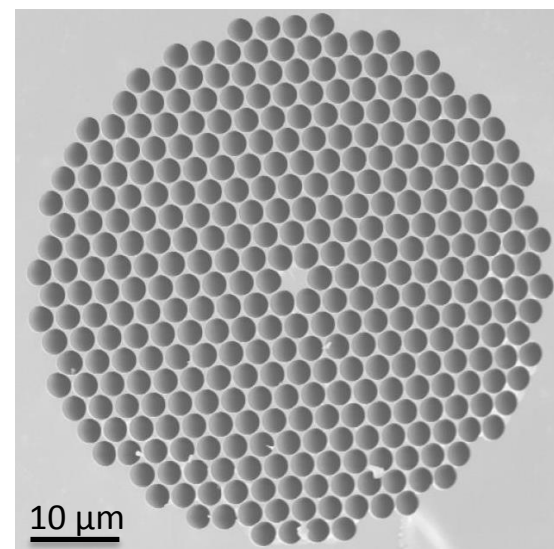
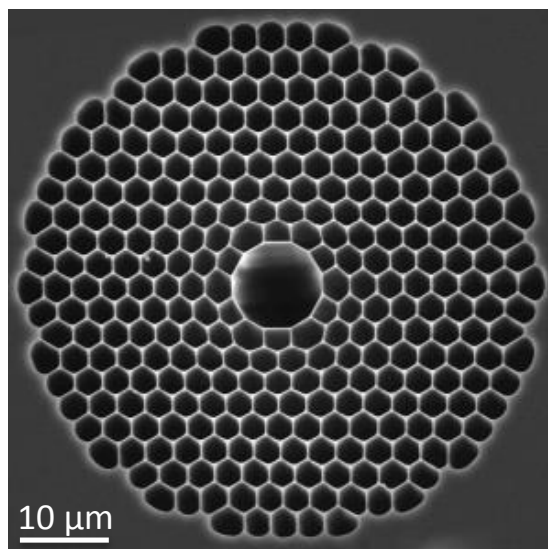
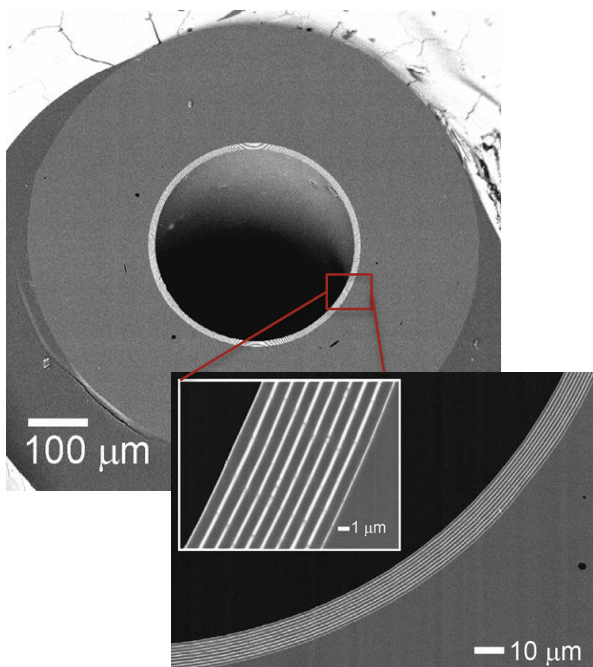


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# Fotonsko kristalna optična vlakna (PCF)

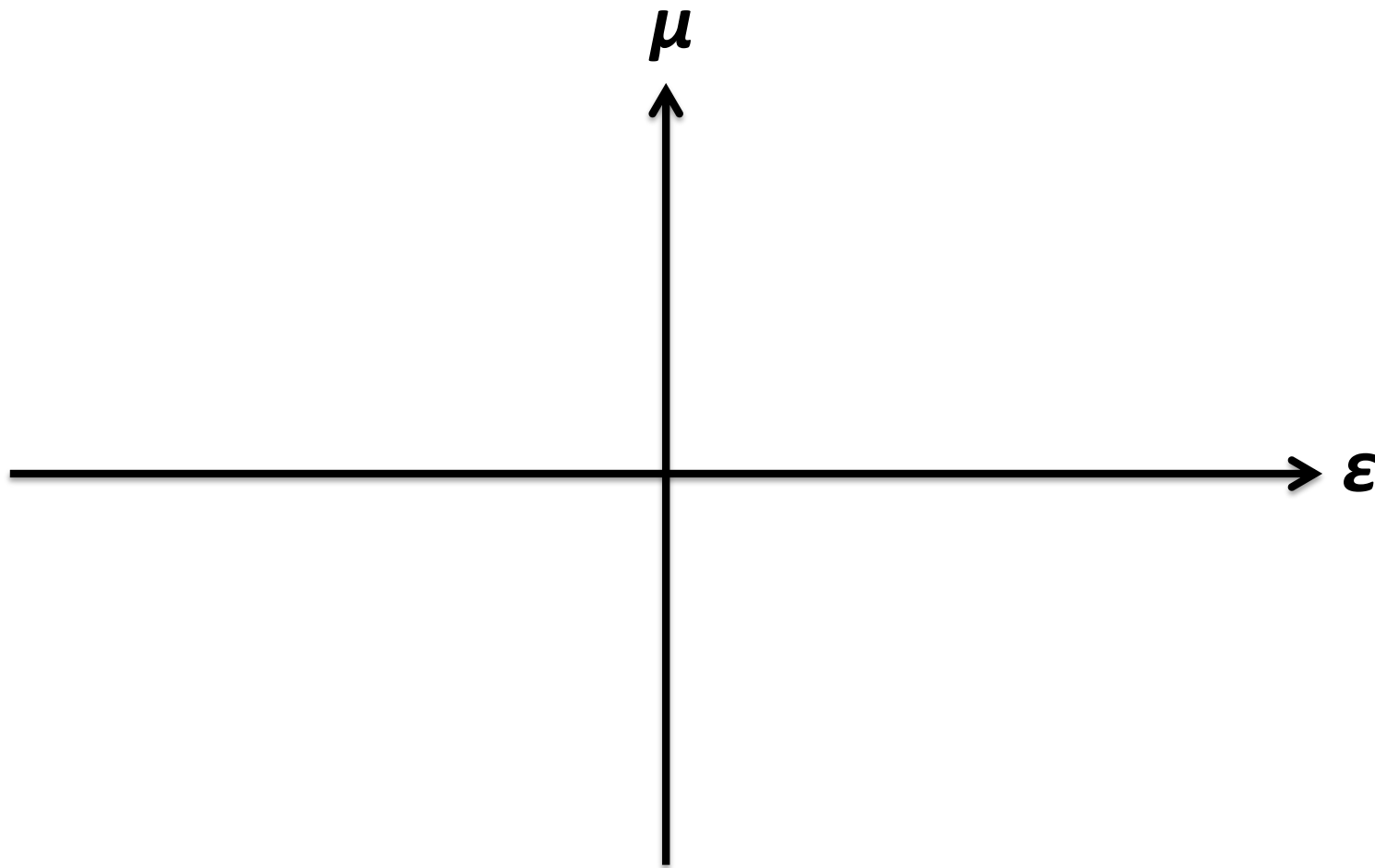
## ▪ Izvedbe

- › Zračna sredica, obdana s koncentrično dielektrično PC strukturo
- › Zračna sredica, obdana z luknjičasto dielektrično PC strukturo
- › Dielektrična sredica, obdana z luknjičasto dielektrično PC strukturo

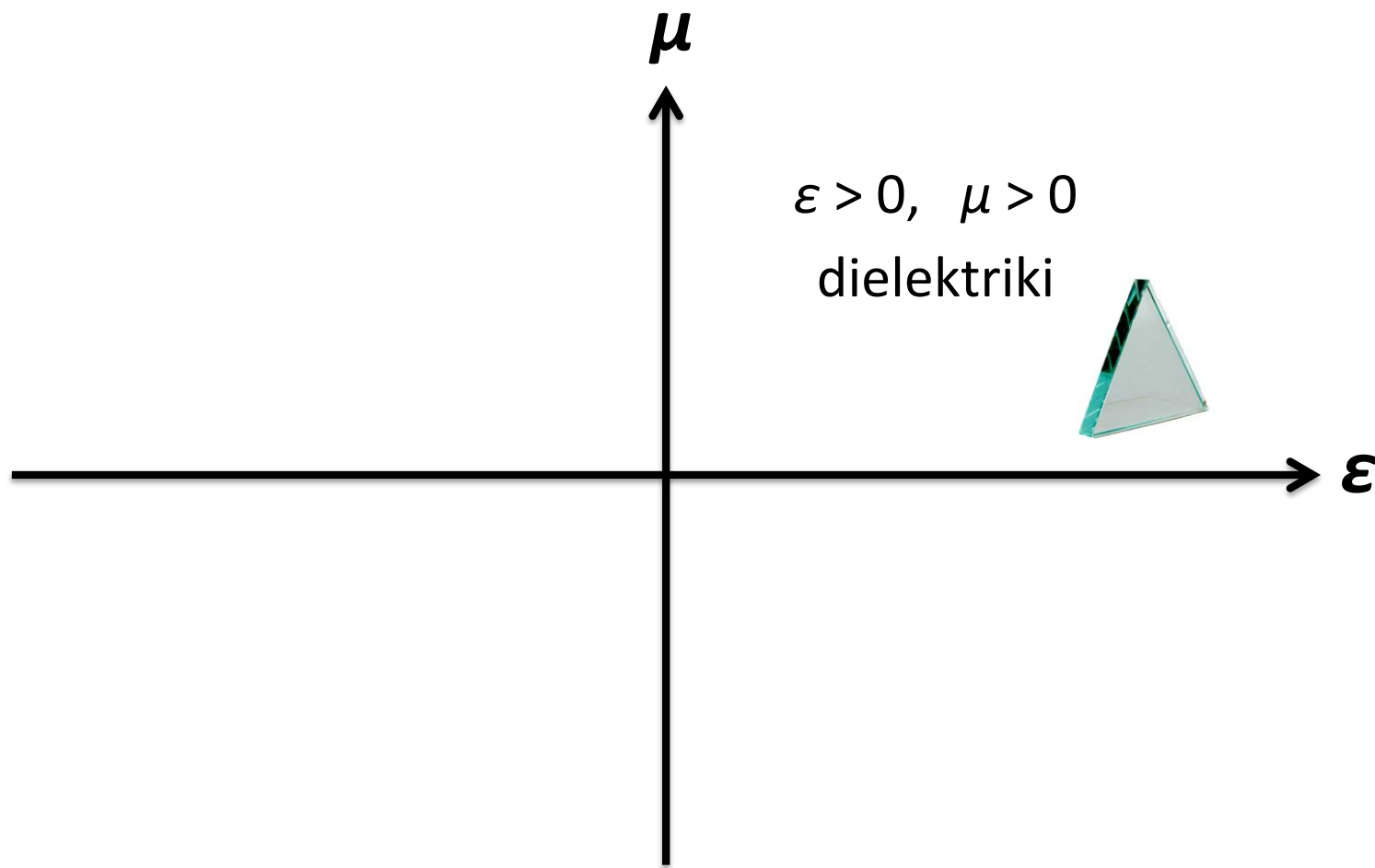


vir: MIT

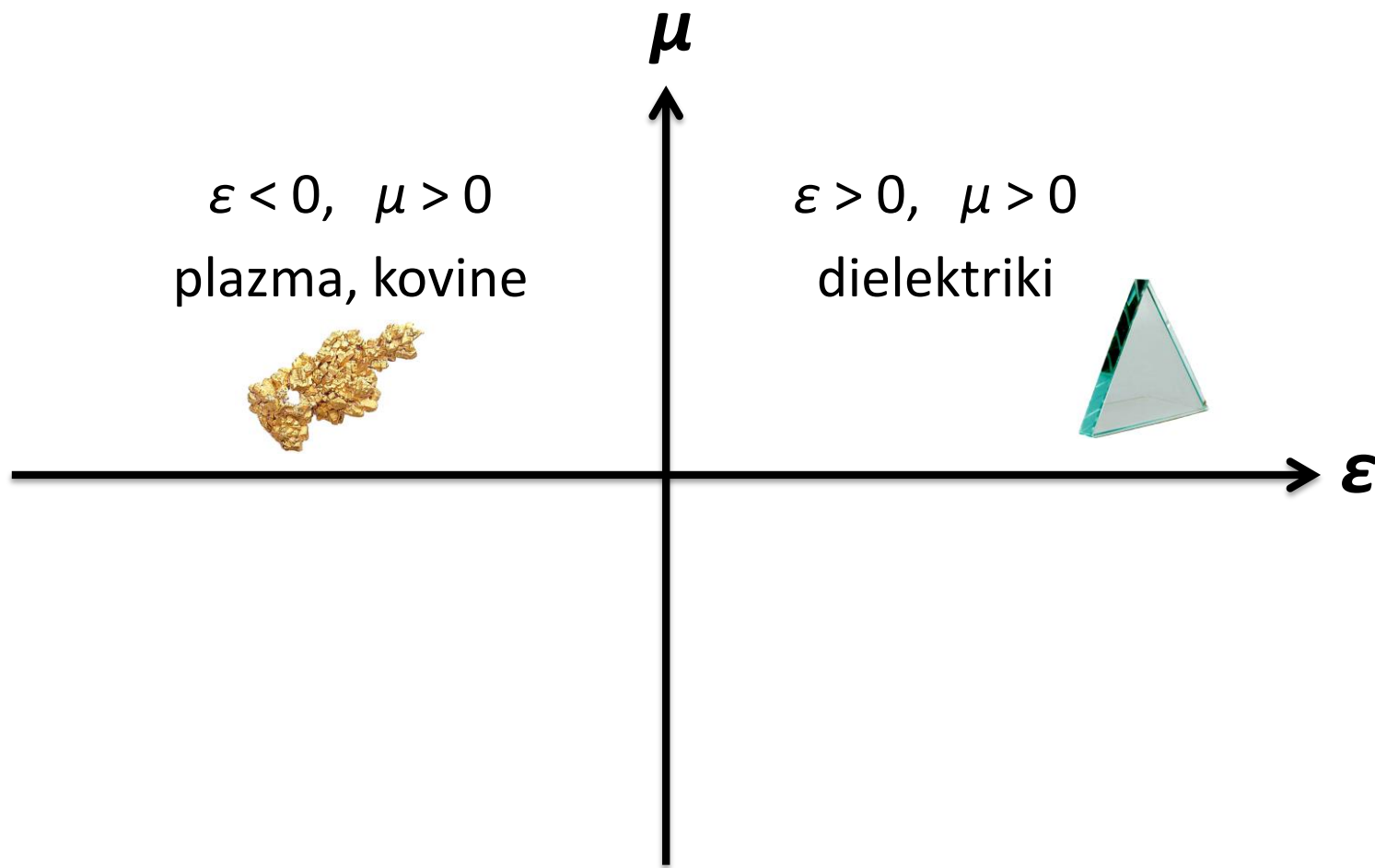
# Razvrstitev materialov



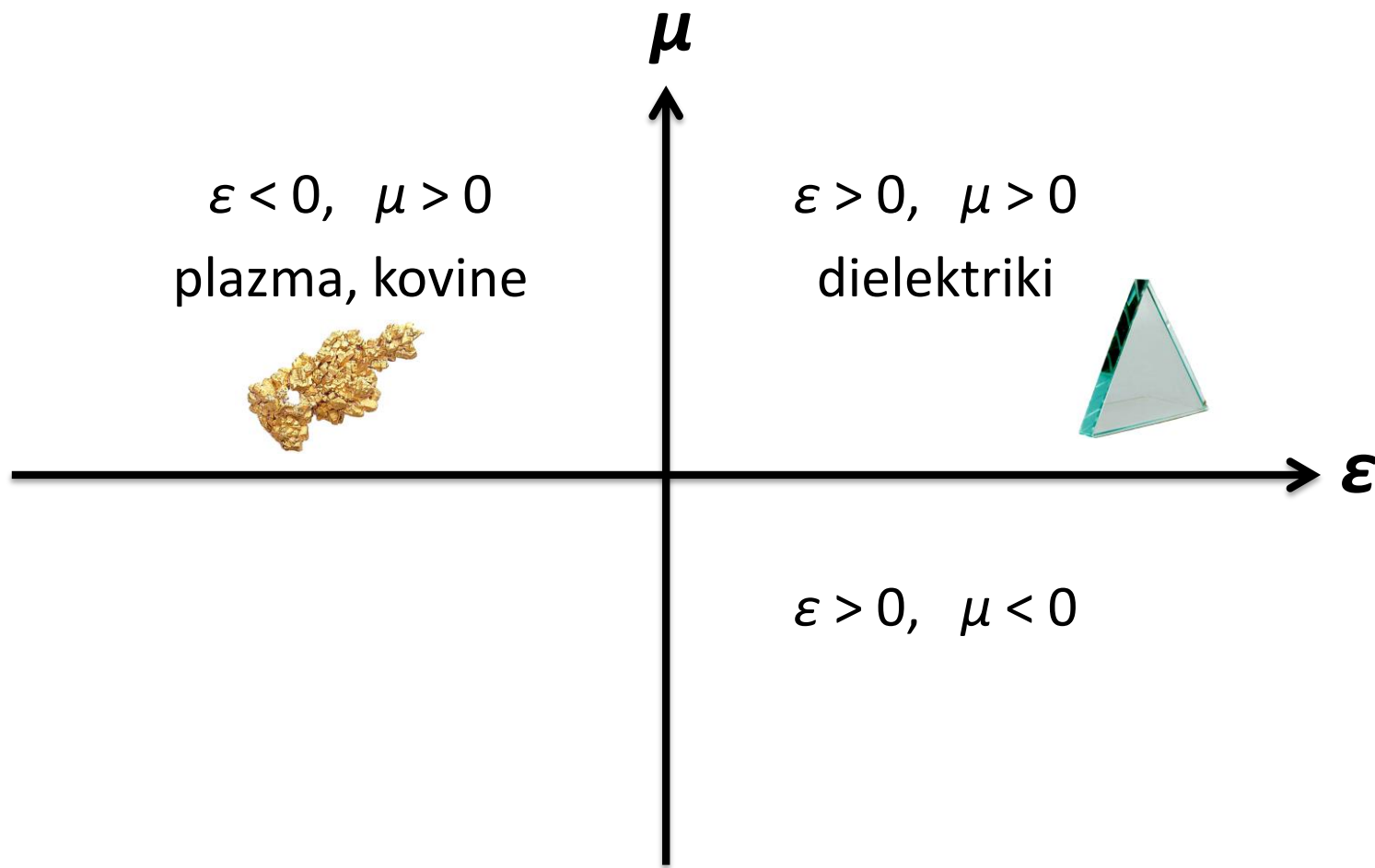
# Razvrstitev materialov



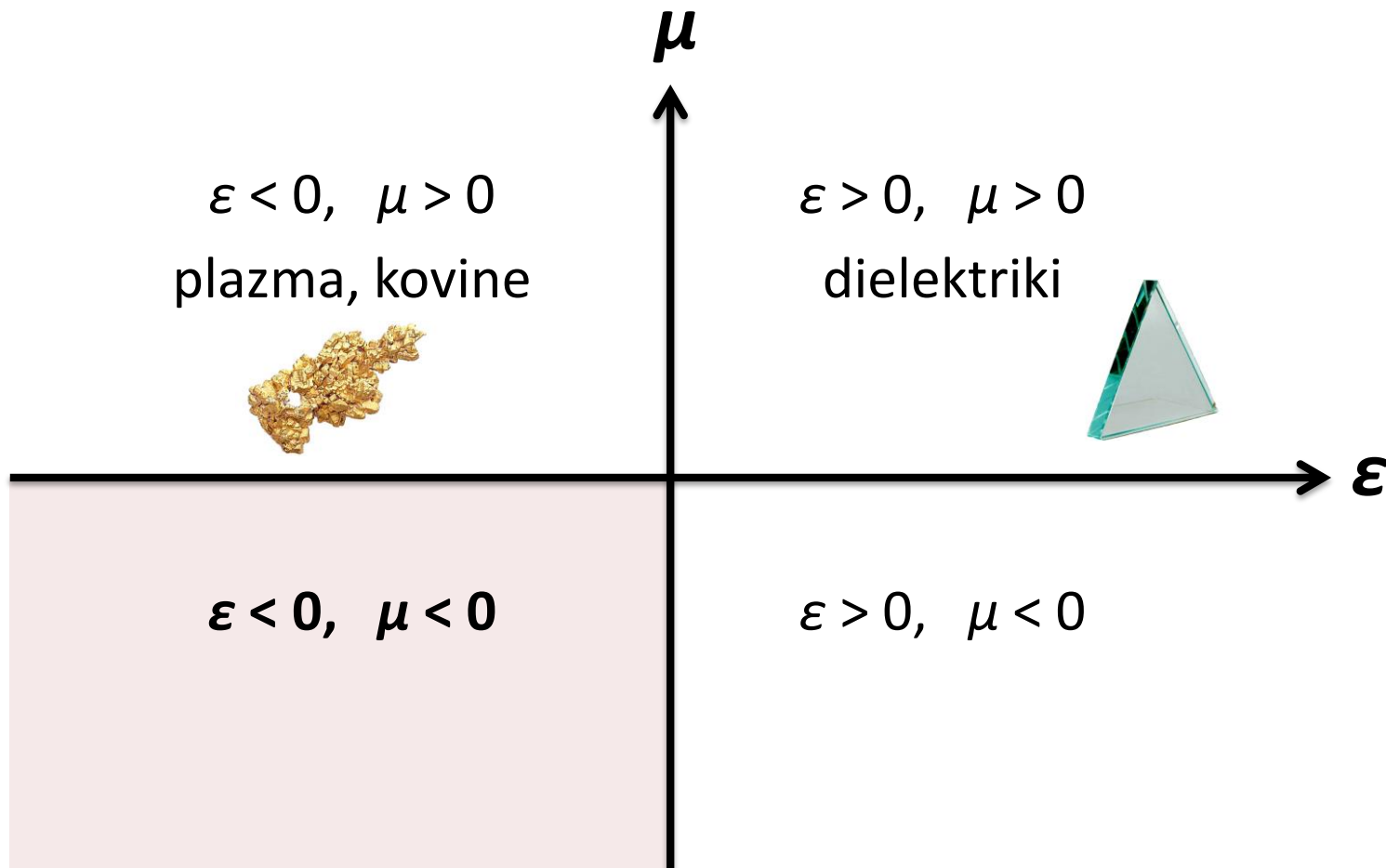
# Razvrstitev materialov



# Razvrstitev materialov

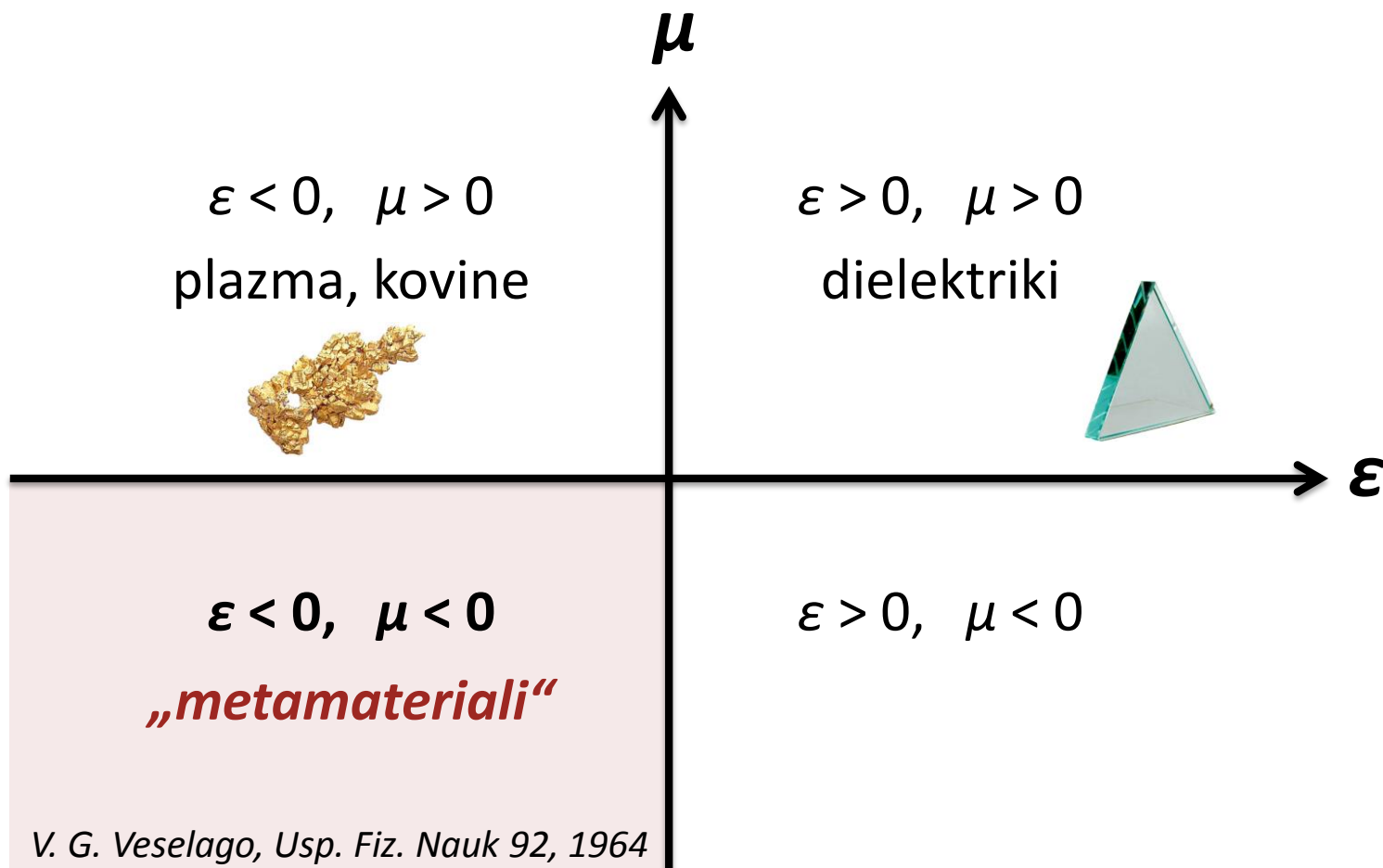


# Razvrstitev materialov



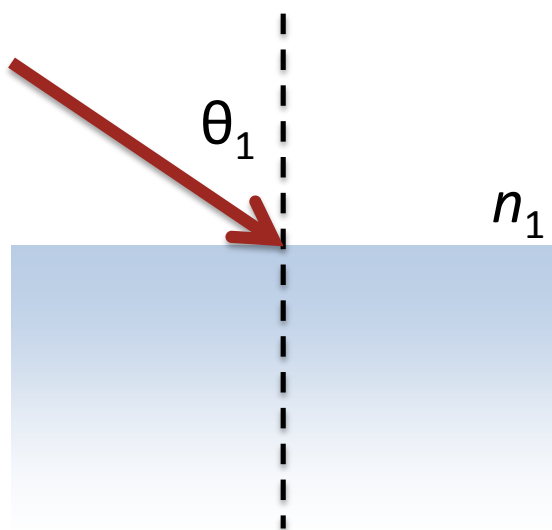


# Razvrstitev materialov



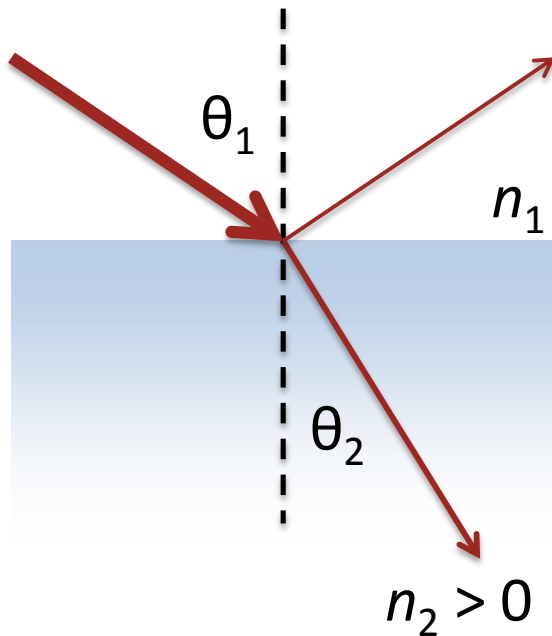
# Metamateriali in negativni lomni količnik

$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{n_2}{n_1}$$



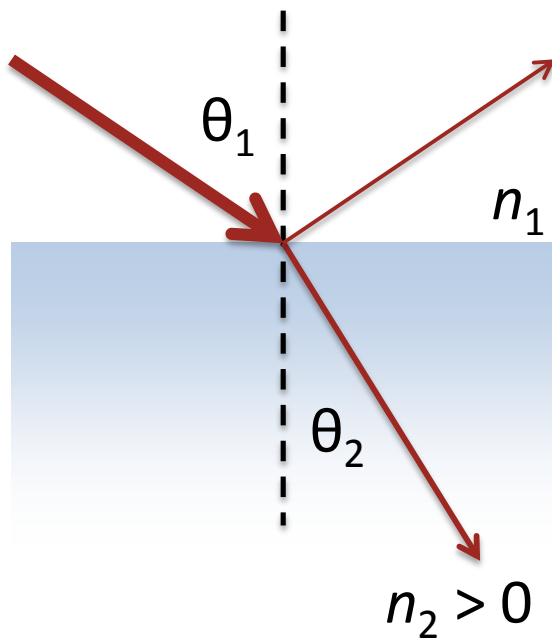
# Metamateriali in negativni lomni količnik

$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{n_2}{n_1}$$



# Metamateriali in negativni lomni količnik

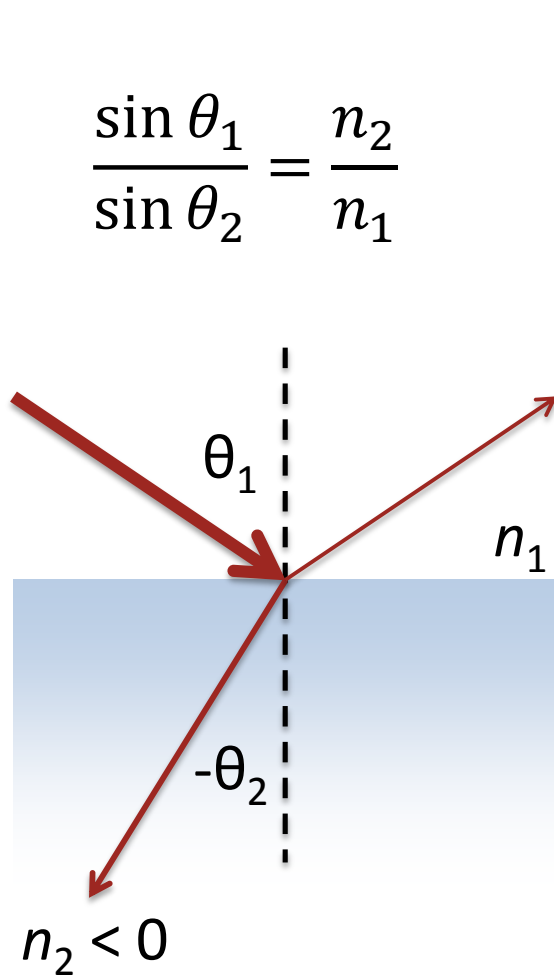
$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{n_2}{n_1}$$



$n > 0$



# Metamateriali in negativni lomni količnik

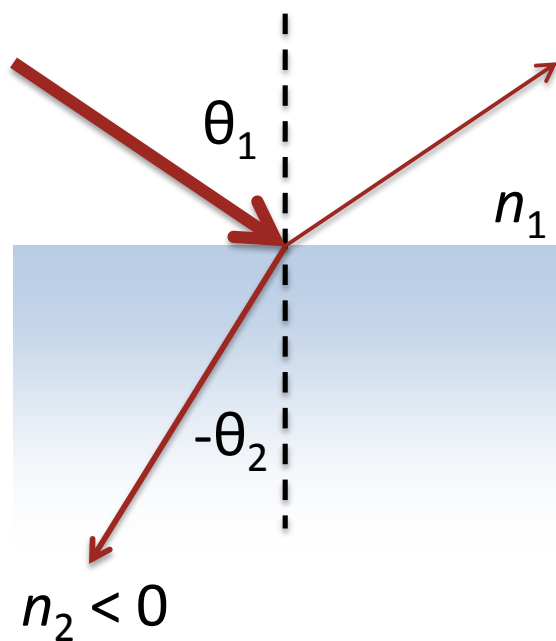


$n > 0$



# Metamateriali in negativni lomni količnik

$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{n_2}{n_1}$$



$n > 0$

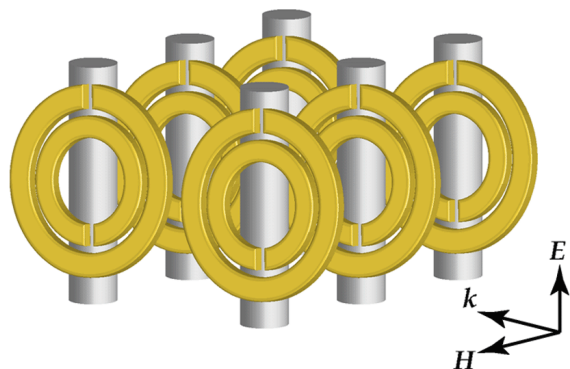


$n < 0$

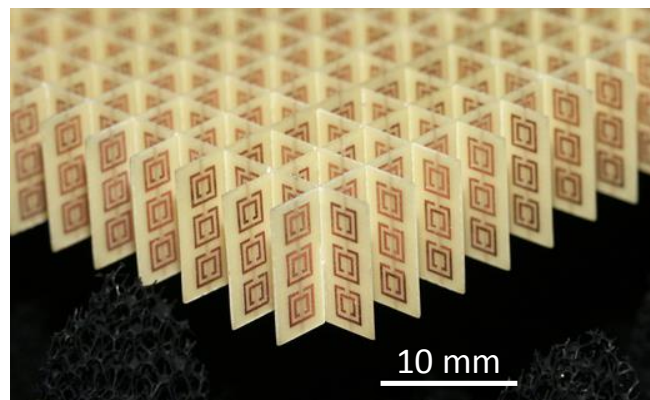


vir: TU Wien

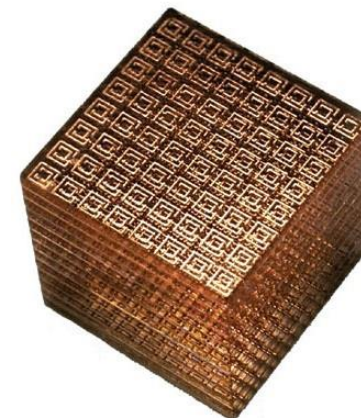
# Metamateriali v mikrovalovnem območju



vir: Pendry, *IEEE T. Microw. Theory* 47, 1999

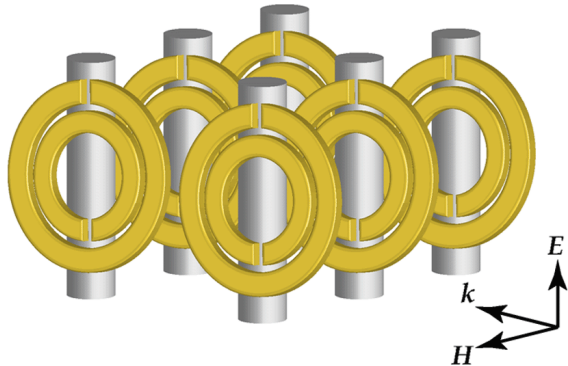


vir: Smith, *Phys. Rev. Lett* 84, 2001

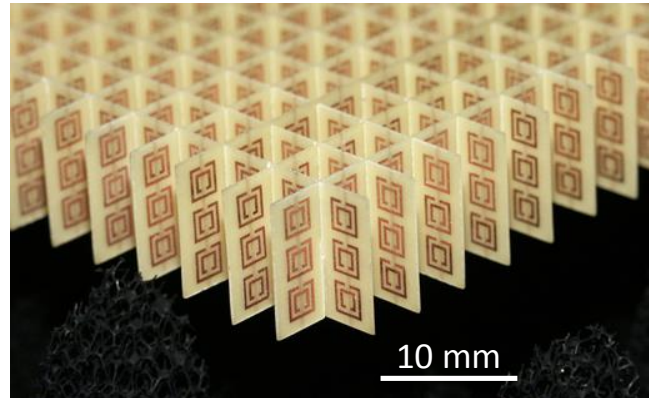


vir: Pendry, *Physics Today*, 2003

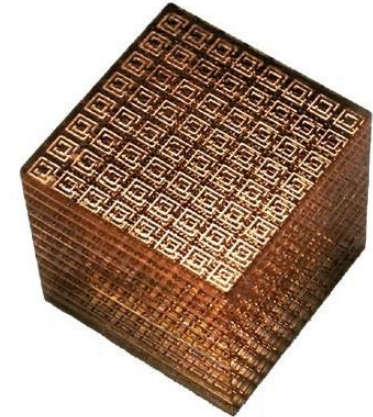
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vir: Pendry, *IEEE T. Microw. Theory* 47, 1999

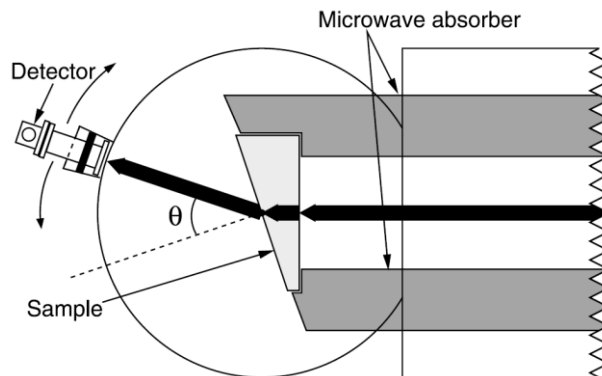
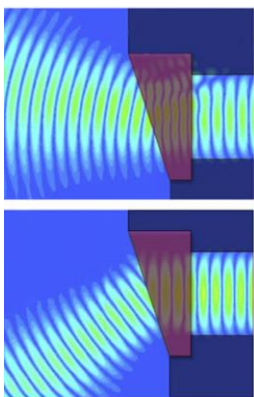


vir: Smith, *Phys. Rev. Lett* 84, 2001

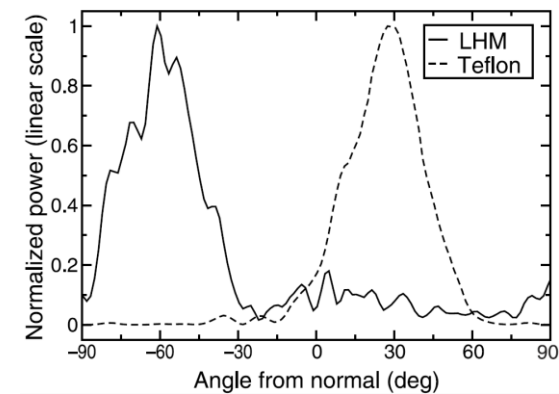


vir: Pendry, *Physics Today*, 2003

## ▪ Eksperiment pri 10.5 GHz



vir: Shelby, *Science* 292, 2001





# Metamateriali v nanovalovnem območju

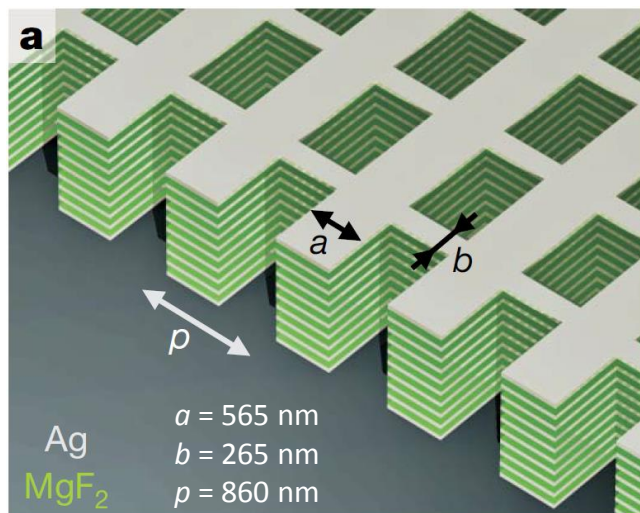
## ■ Izzivi

- › Izjemno majhne dimenzije osnovnih celic (manjše od valovne dolžine)
- › Potreba po 3D strukturah; zahtevna izdelava

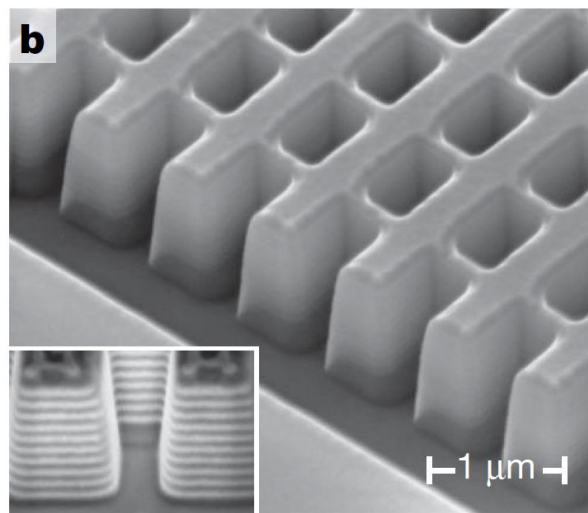
# Metamateriali v nanovalovnem območju

## ■ Izzivi

- › Izjemno majhne dimenzije osnovnih celic (manjše od valovne dolžine)
- › Potreba po 3D strukturah; zahtevna izdelava



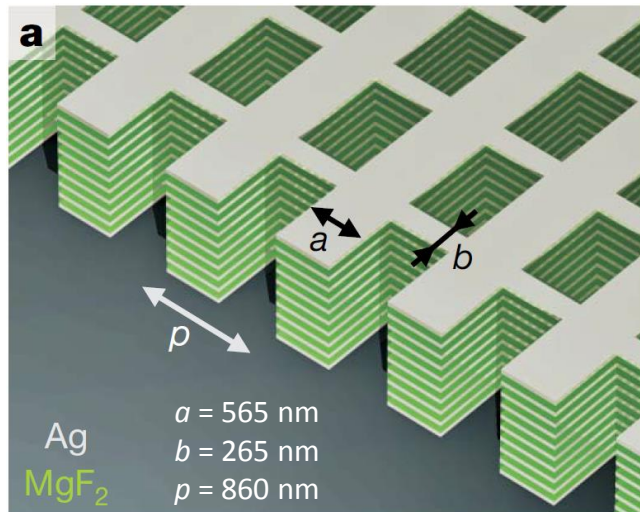
vir: Valentine, *Nature Letters* 455, 2008



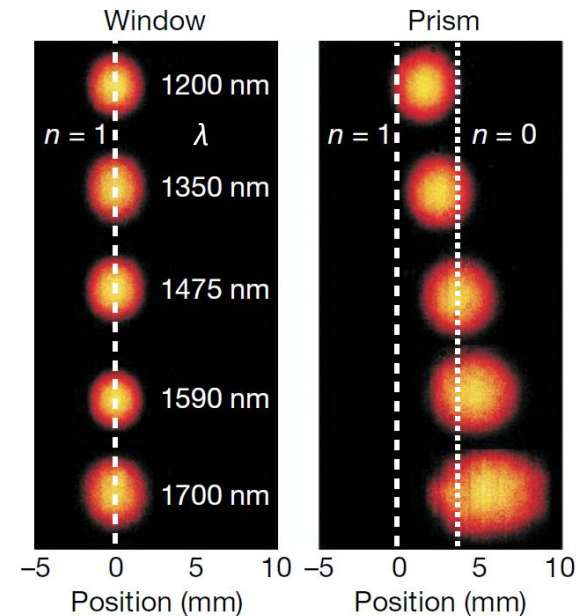
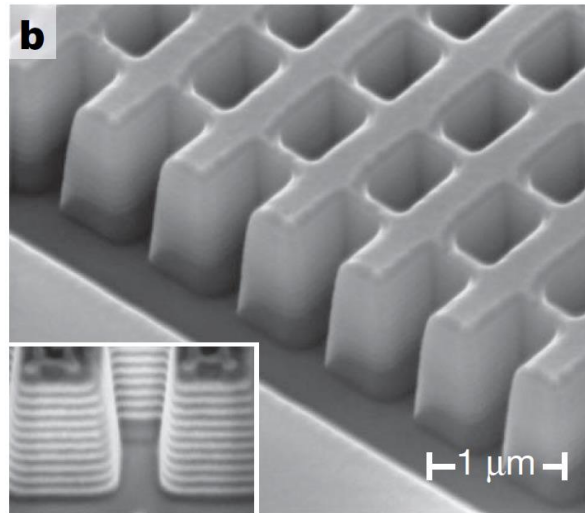
# Metamateriali v nanovalovnem območju

## ■ Izzivi

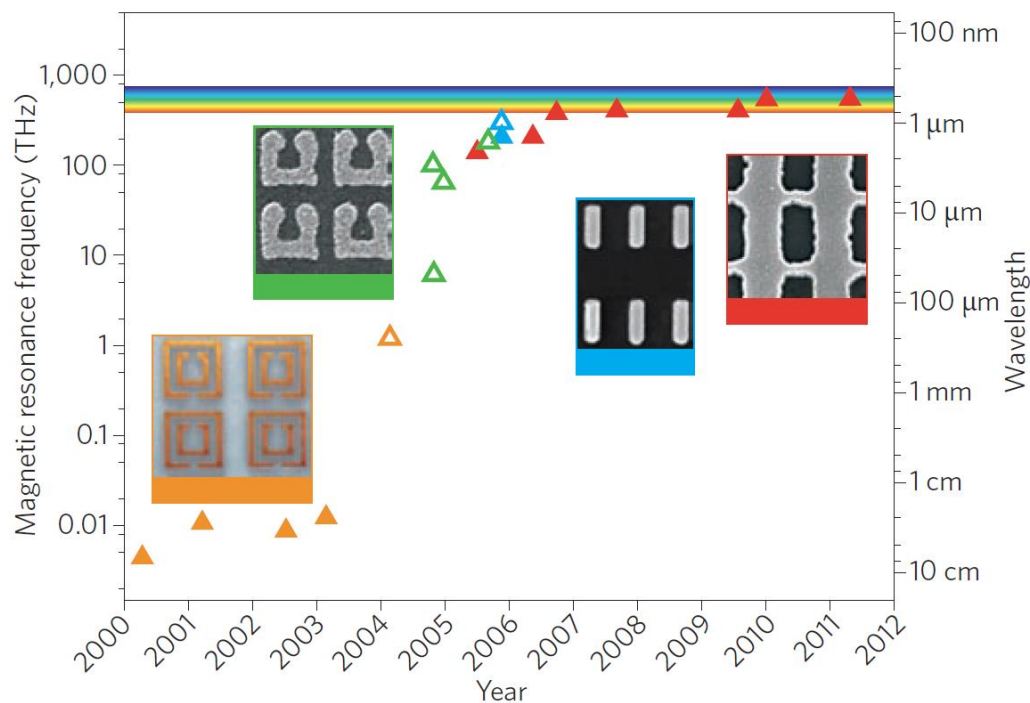
- › Izjemno majhne dimenzije osnovnih celic (manjše od valovne dolžine)
- › Potreba po 3D strukturah; zahtevna izdelava



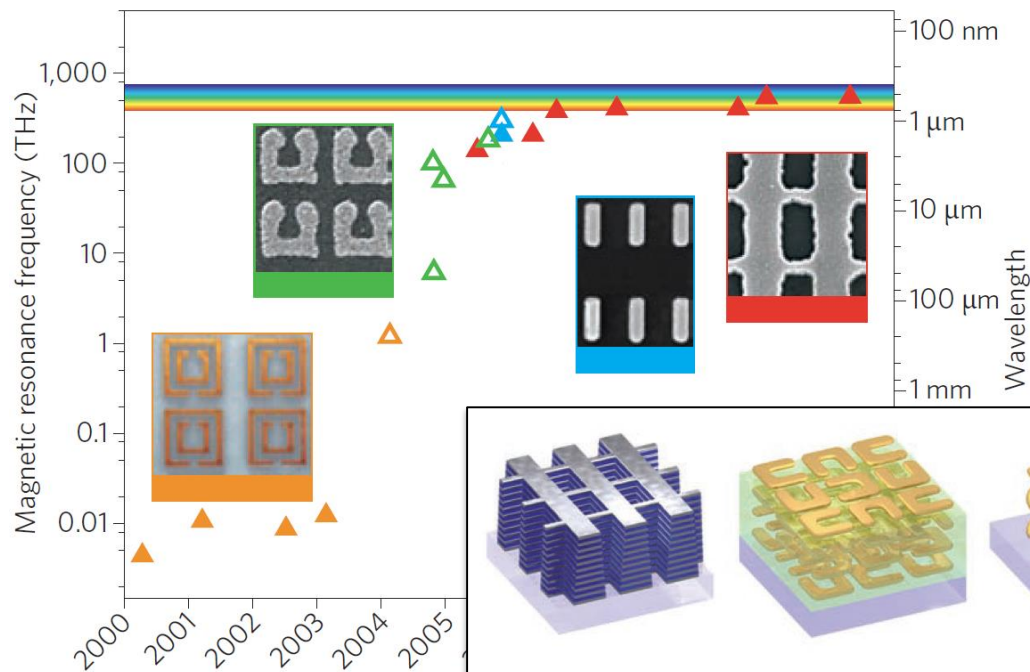
vir: Valentine, Nature Letters 455, 2008



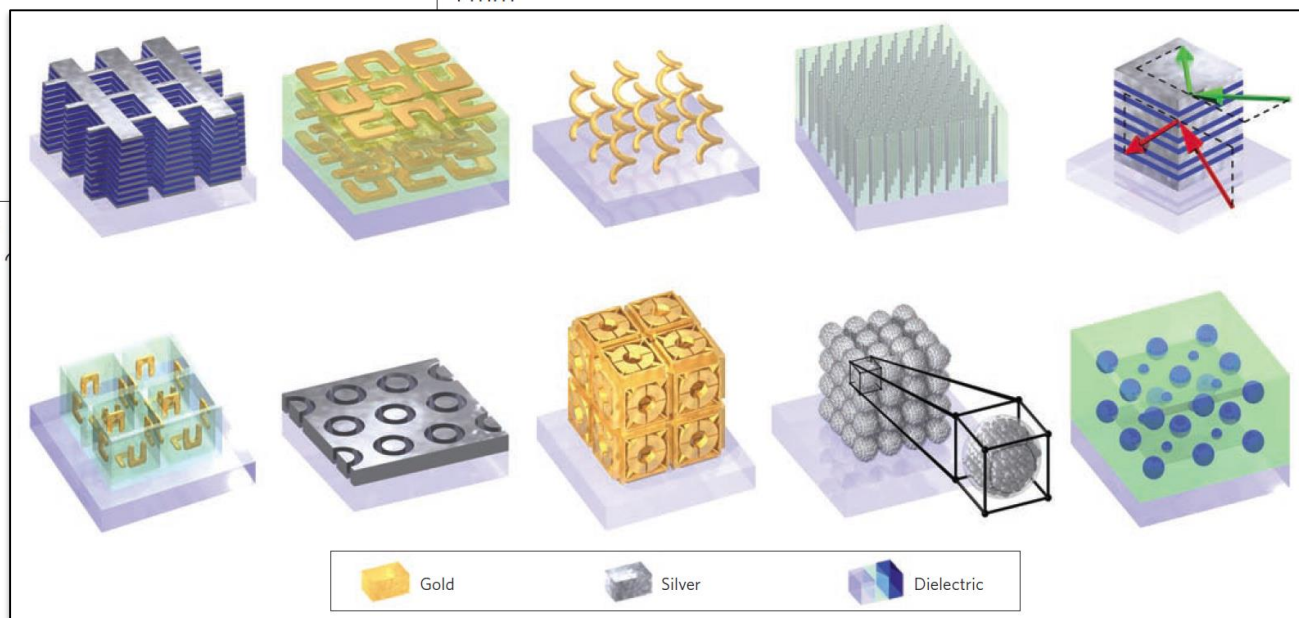
# Metamateriali v nanovalovnem območju



# Metamateriali v nanovalovnem območju



vir: Soukoulis, Nature Photonics, 2011

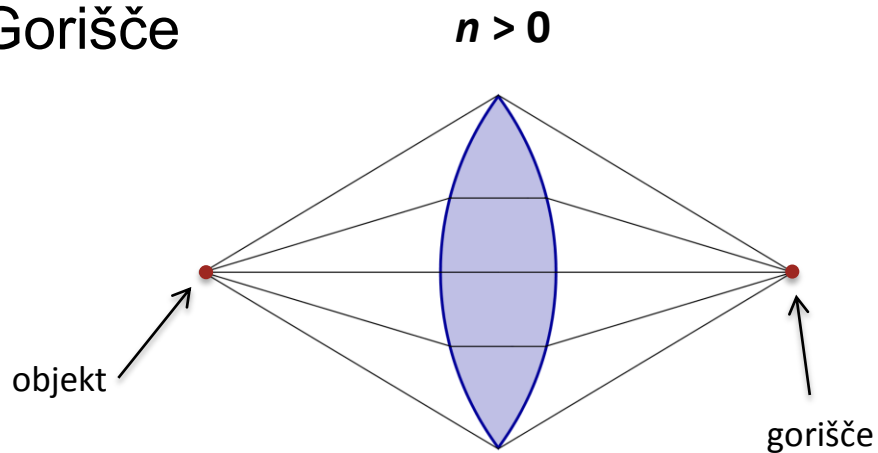


# Metamateriali – superleča

- Gorišče
- Ločljivost

# Metamateriali – superleča

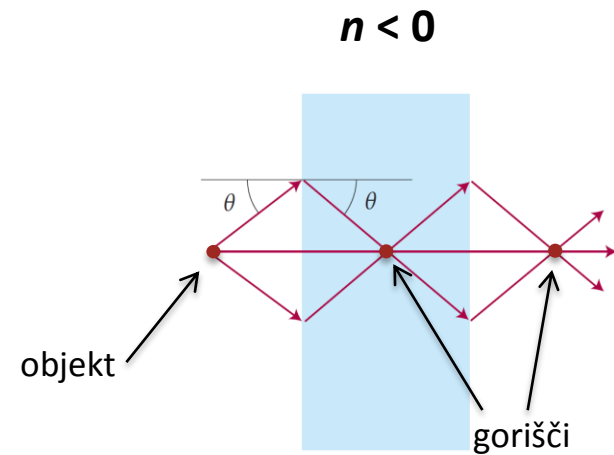
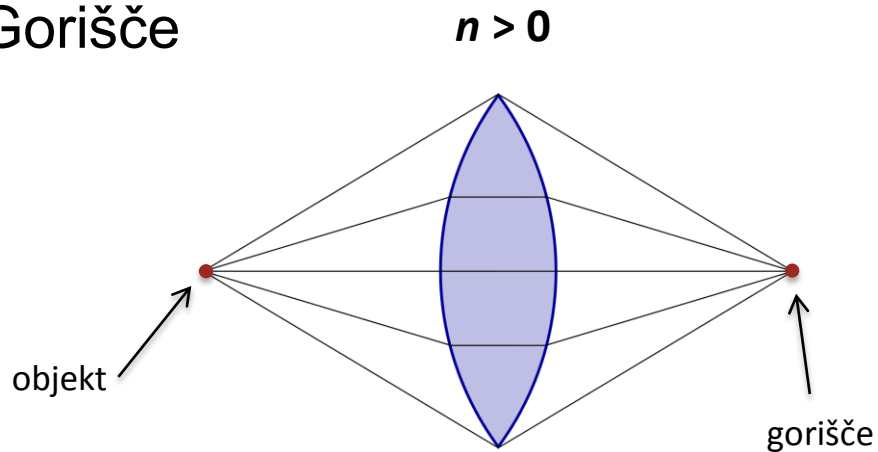
- Gorišče



- Ločljivost

# Metamateriali – superleča

## ▪ Gorišče

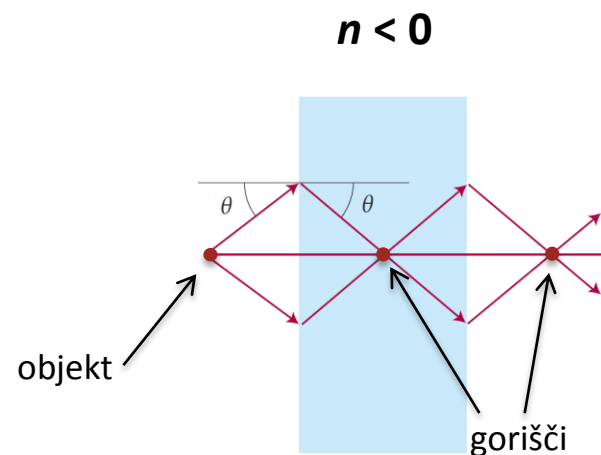
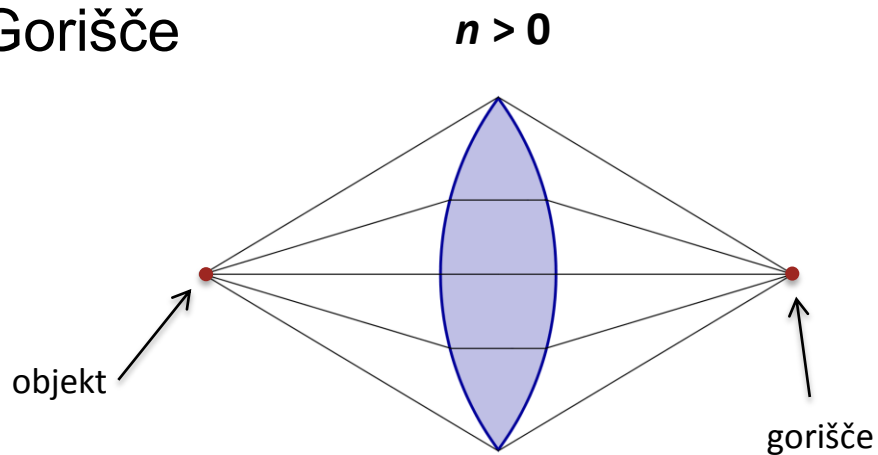


## ▪ Ločljivost

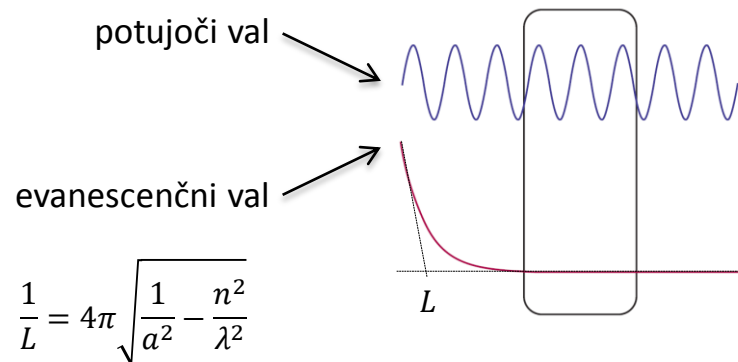


# Metamateriali – superleča

## ▪ Gorišče

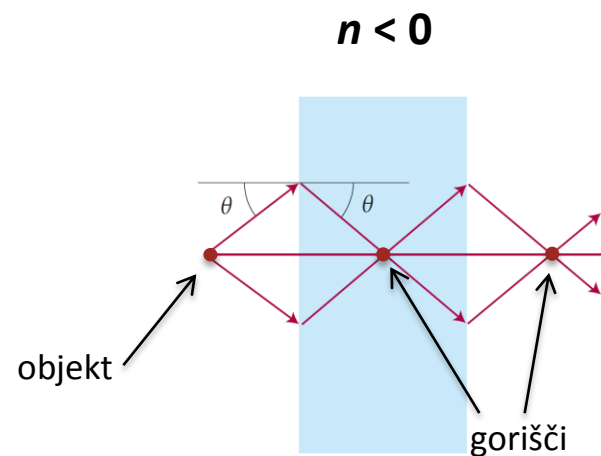
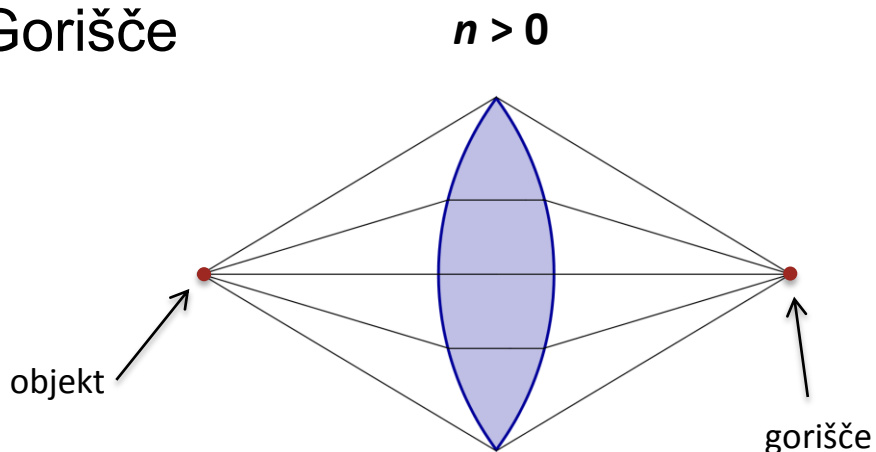


## ▪ Ločljivost

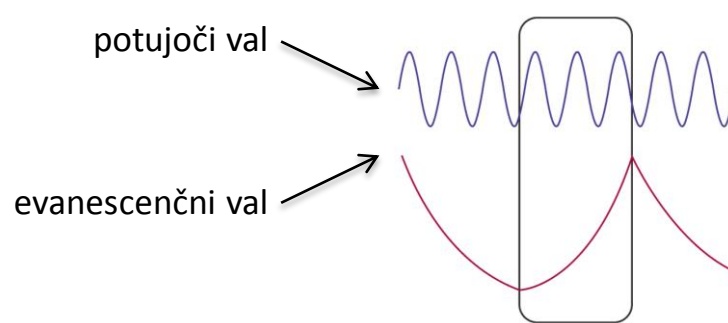
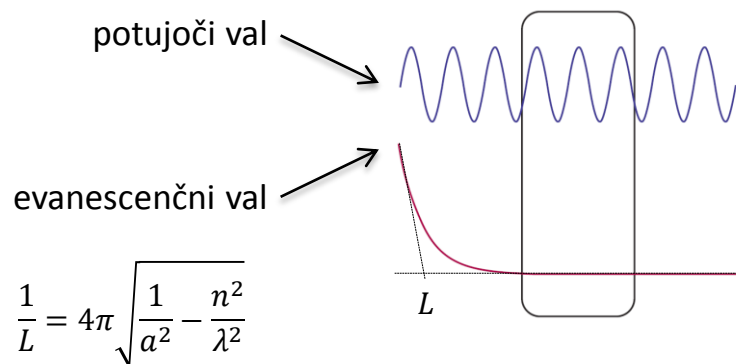


# Metamateriali – superleča

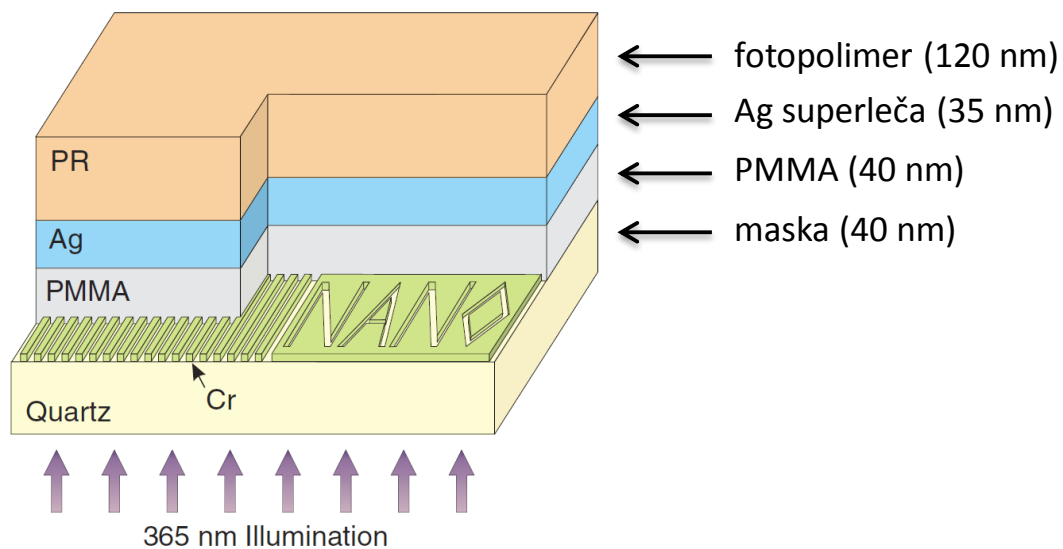
## ▪ Gorišče



## ▪ Ločljivost



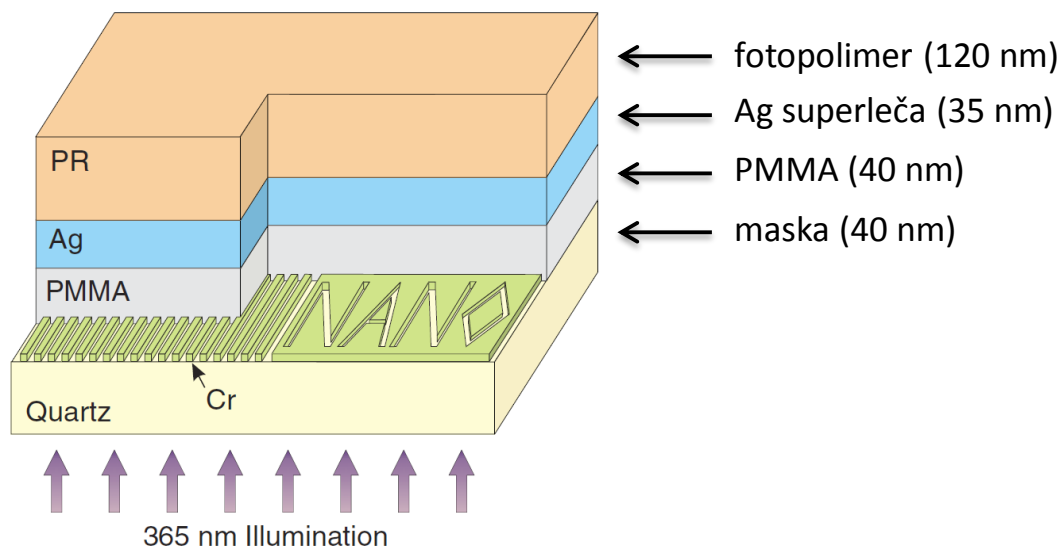
# Metamateriali – superleča



← fokusirani ionski snop (40 nm širina črte)

vir: Fang, Science 308, 2005

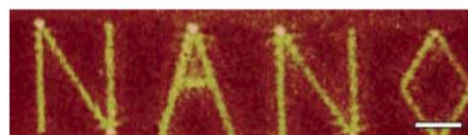
# Metamateriali – superleča



← fokusirani ionski  
snop (40 nm širina črte)



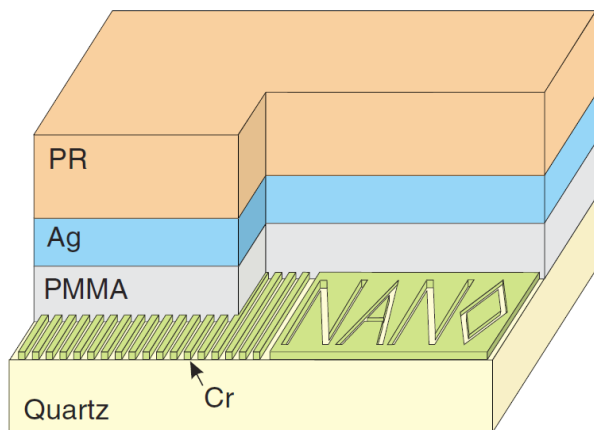
← AFM slike na polimeru  
z Ag superlečo



← AFM slike na polimeru  
brez Ag superleče

vir: Fang, Science 308, 2005

# Metamateriali – superleča



- ← fotopolimer (120 nm)
- ← Ag superleča (35 nm)
- ← PMMA (40 nm)
- ← maska (40 nm)

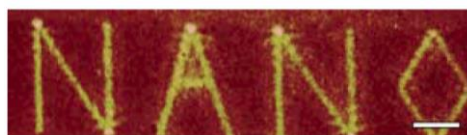
365 nm Illumination



← fokusirani ionski snop (40 nm širina črte)

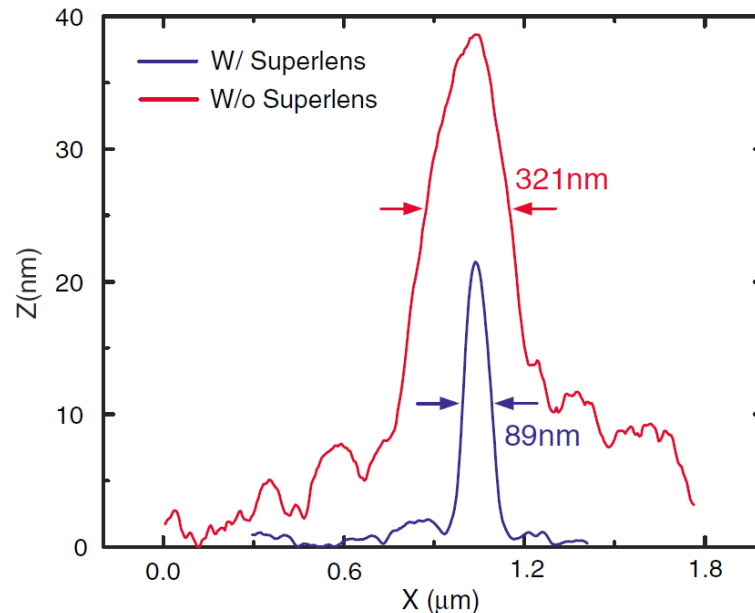


← AFM slike na polimeru z Ag superlečo

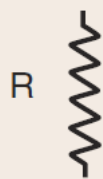
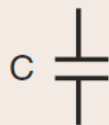


← AFM slike na polimeru brez Ag superleče

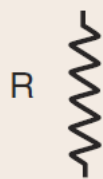
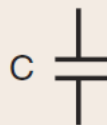
### Ločljivost

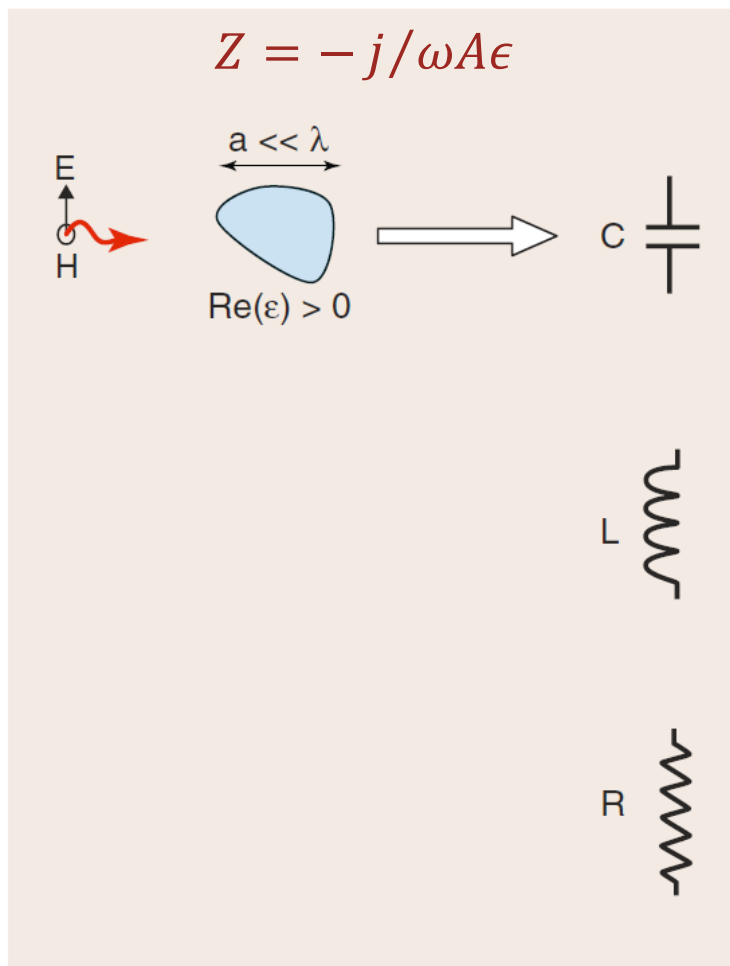


vir: Fang, Science 308, 2005

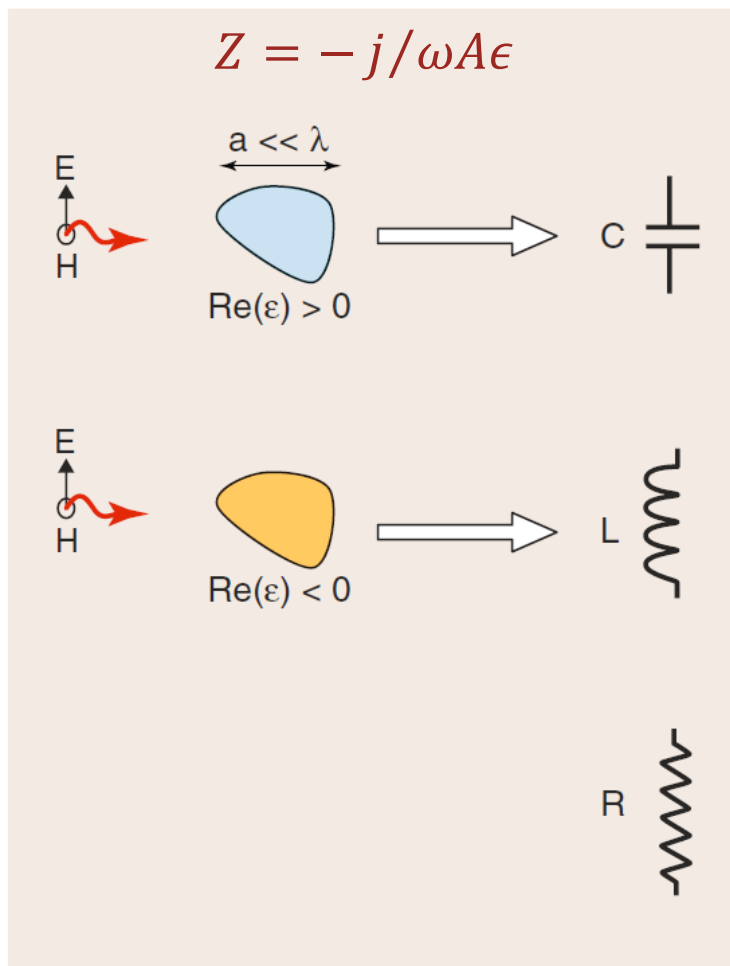


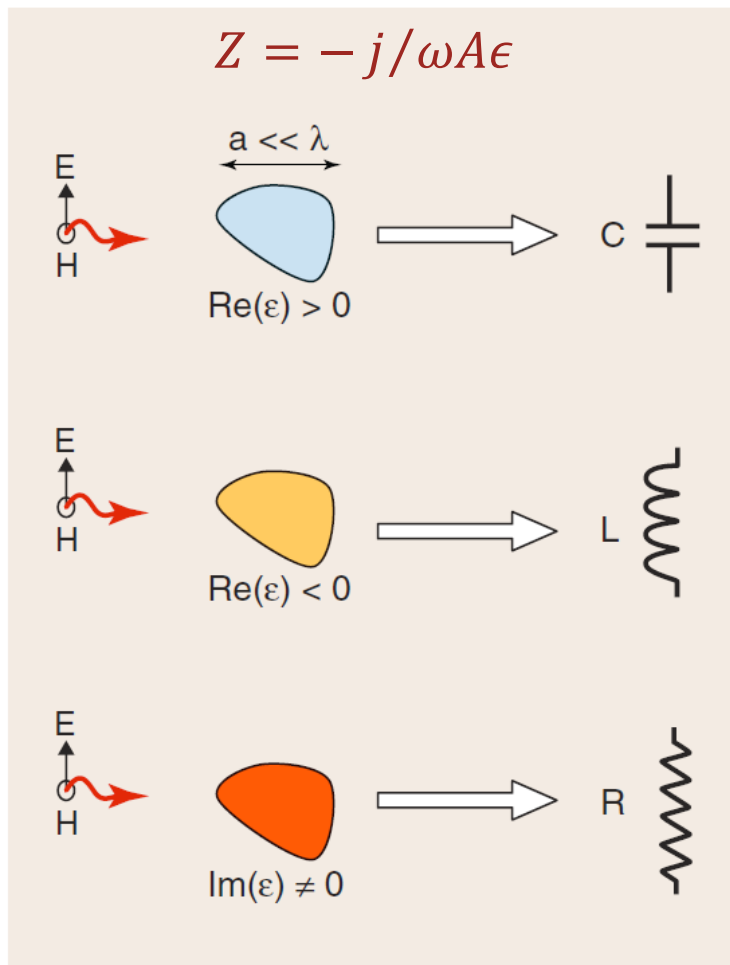
$$Z = -j/\omega A\epsilon$$



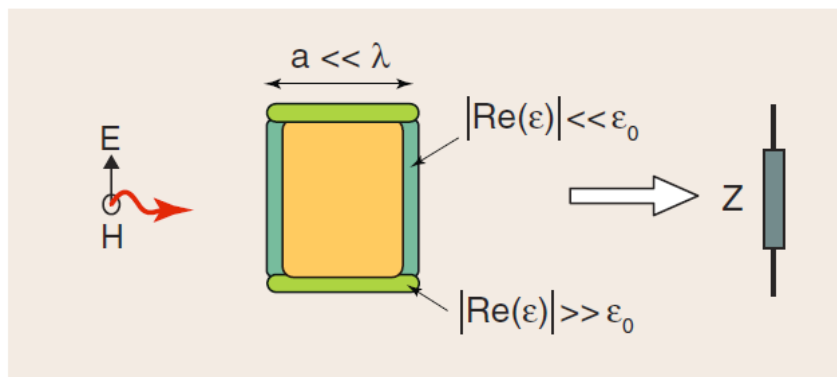
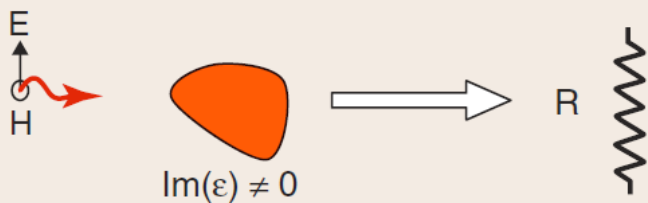
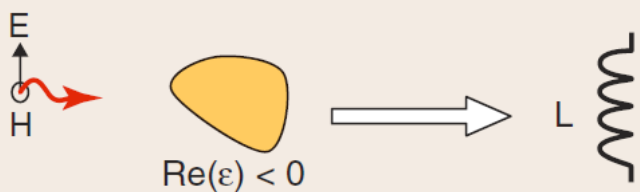
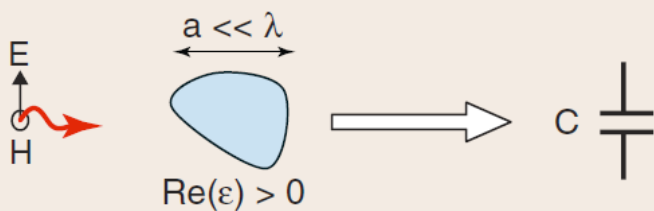




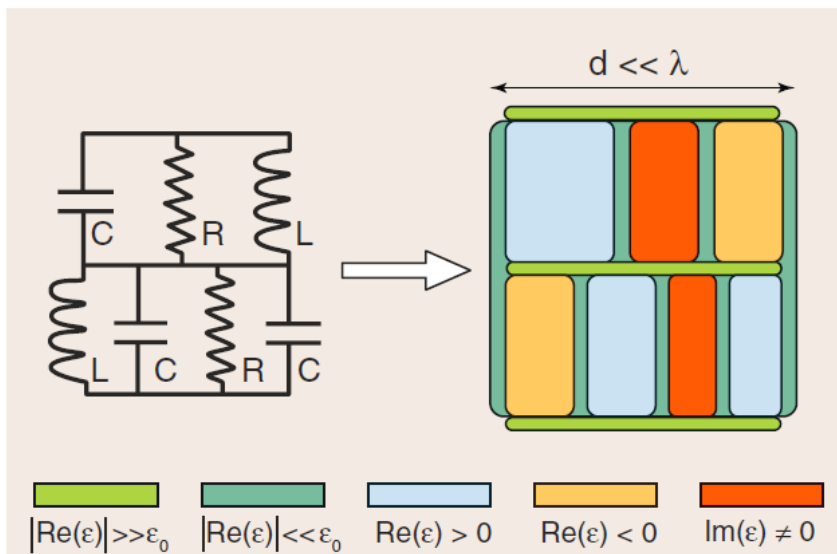
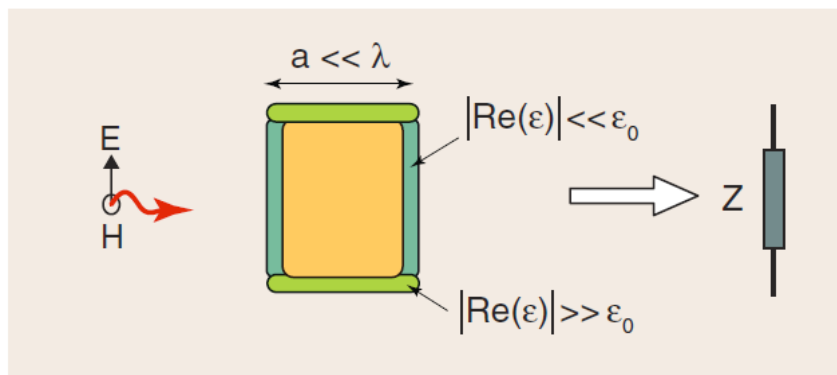
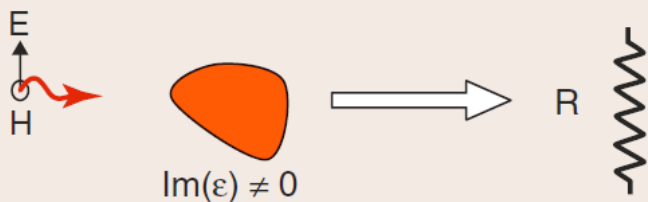
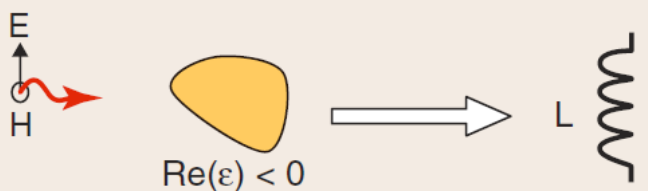
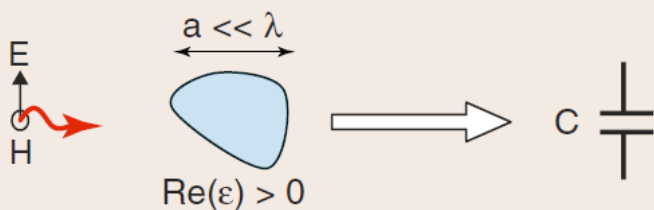




$$Z = -j/\omega A\epsilon$$

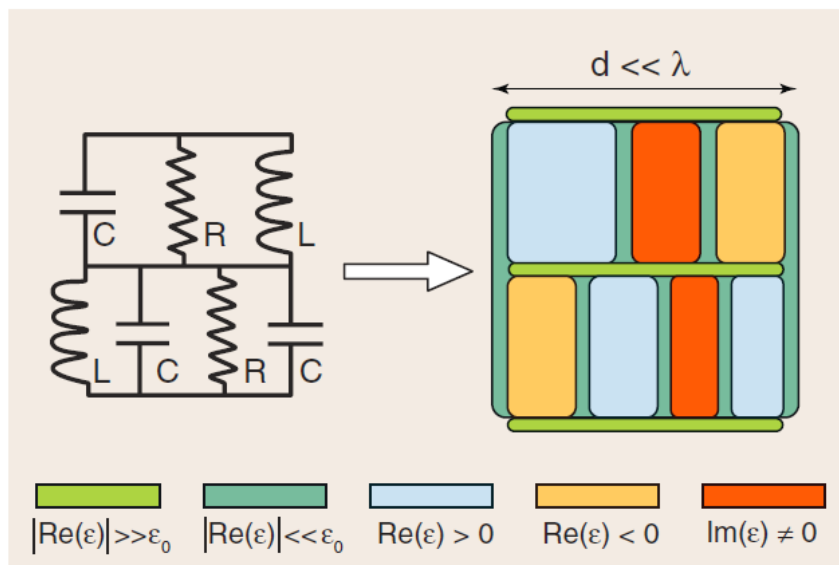
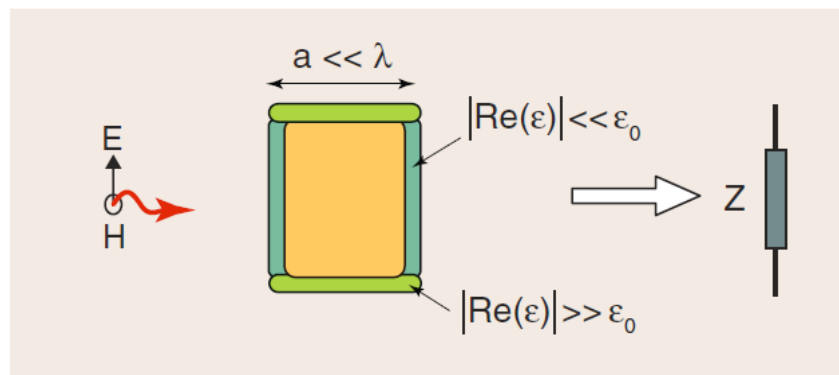
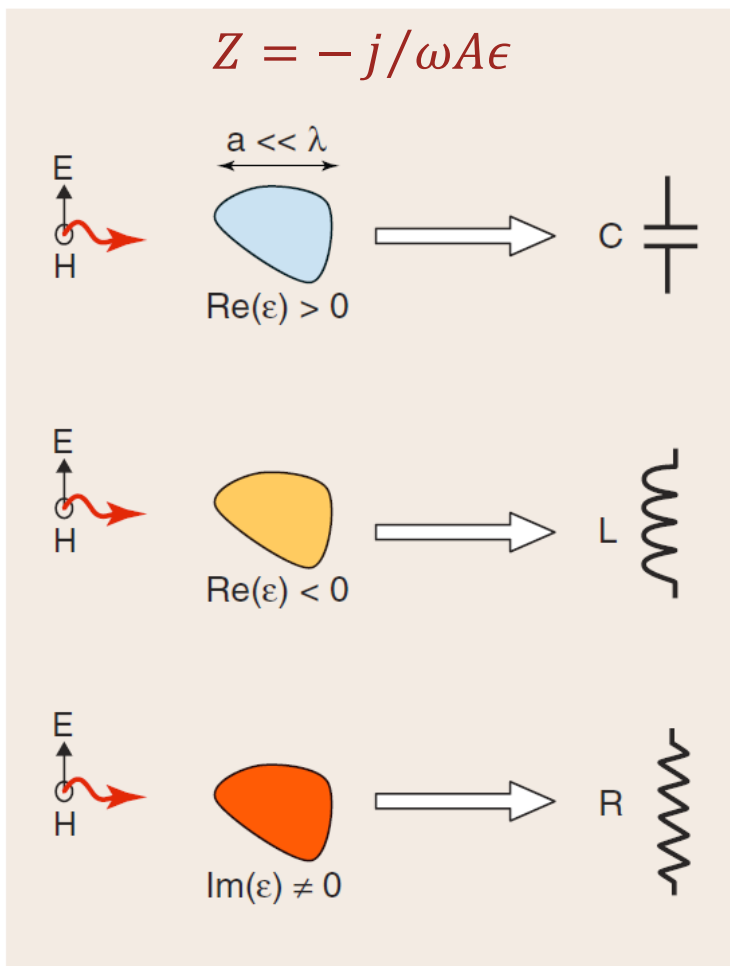


$$Z = -j/\omega A\epsilon$$



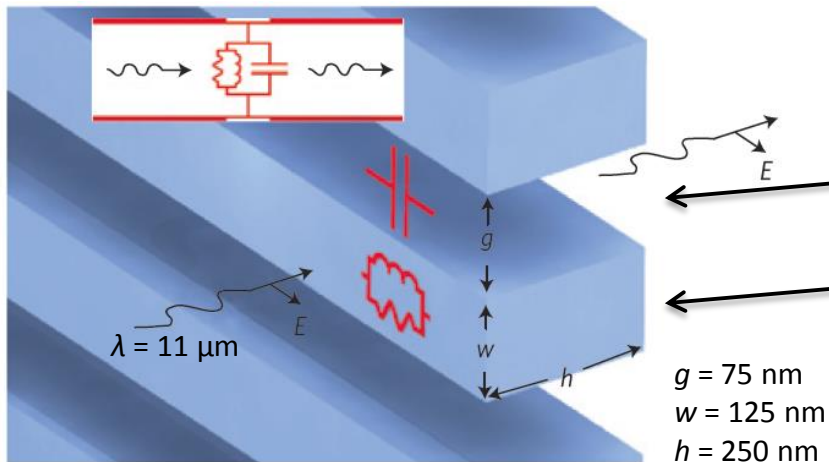
vir: Engheta, Science 317, 2007

# „Metatronika“



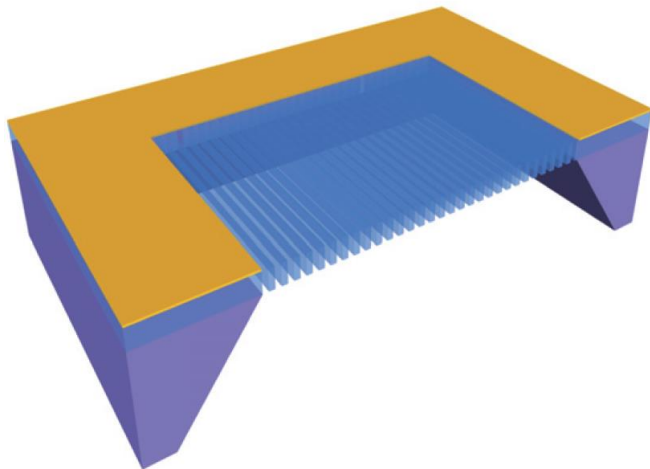
vir: Engheta, Science 317, 2007

## „Metatronika“



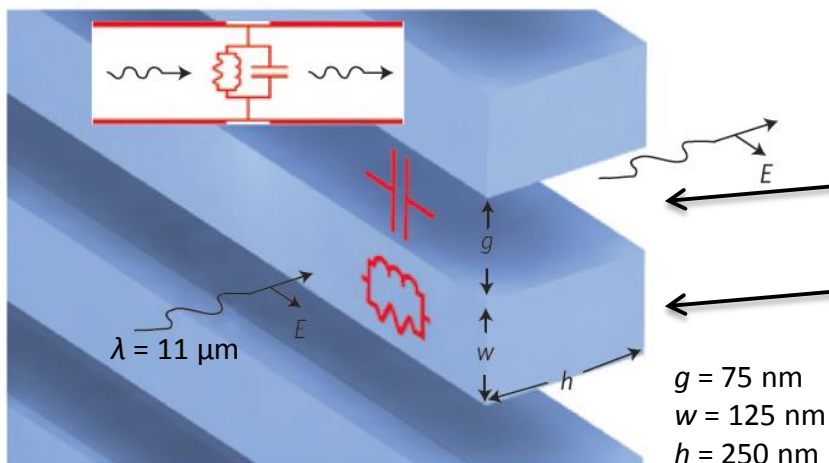
zrak [ $\text{Re}(\epsilon) > 0$ ,  $\text{Im}(\epsilon) = 0$ ]

$\text{Si}_3\text{N}_4$  [ $\text{Re}(\epsilon) < 0$ ,  $\text{Im}(\epsilon) \neq 0$ ]



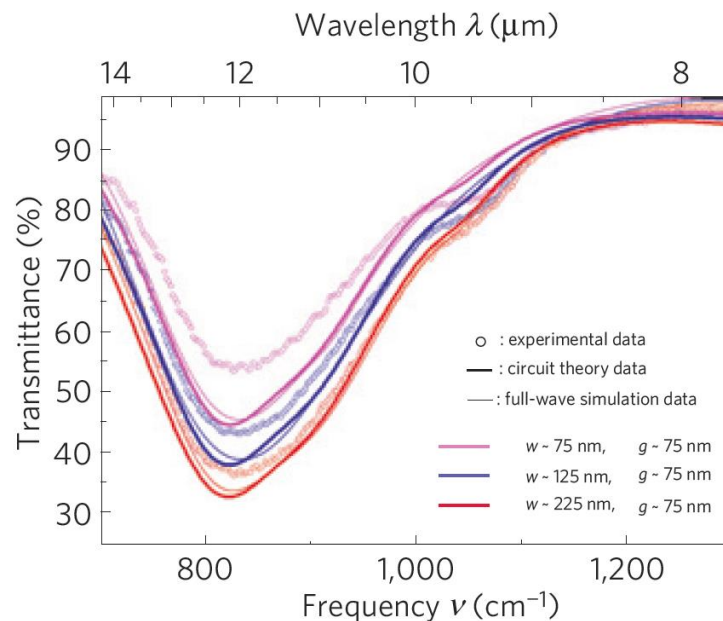
vir: Sun, Nature Materials 11, 2012

# „Metatronika“



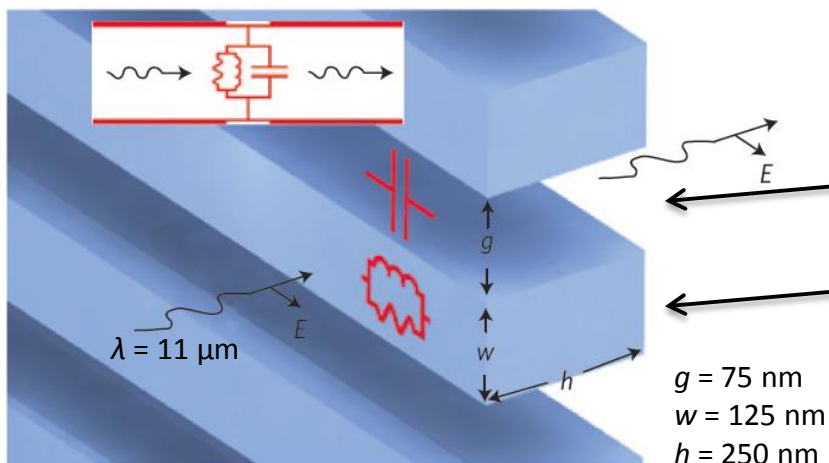
zrak [ $\text{Re}(\epsilon) > 0, \text{Im}(\epsilon) = 0$ ]

$\text{Si}_3\text{N}_4$  [ $\text{Re}(\epsilon) < 0, \text{Im}(\epsilon) \neq 0$ ]



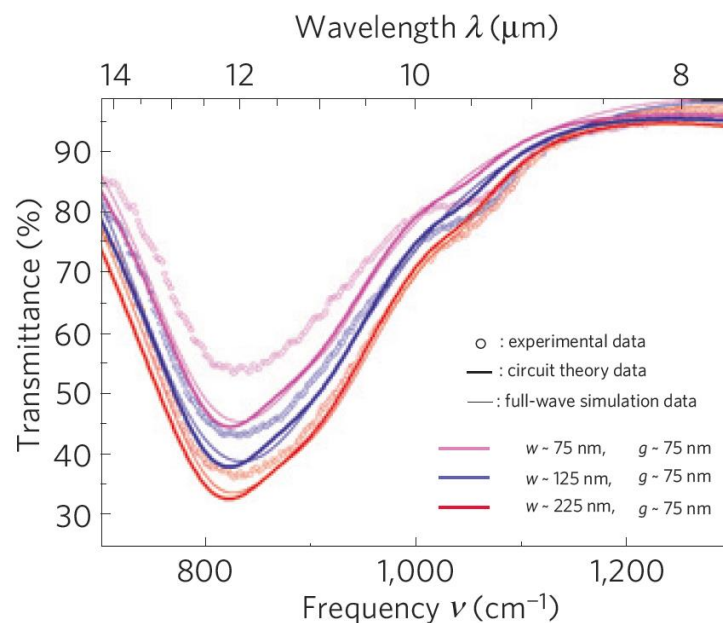
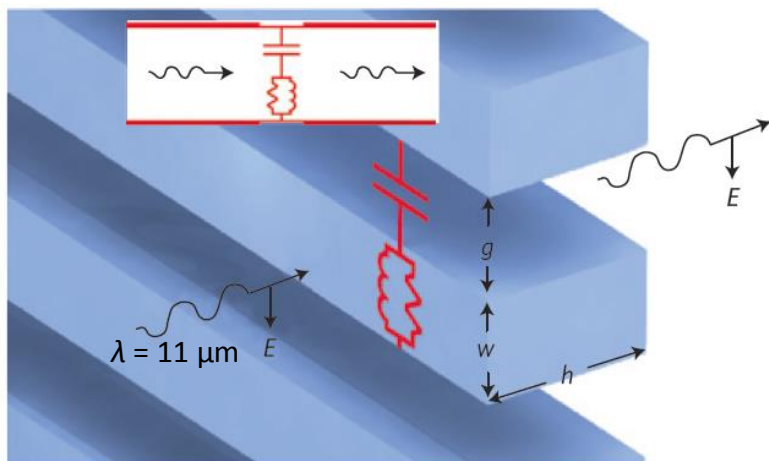
vir: Sun, Nature Materials 11, 2012

# „Metatronika“



zrak [ $\text{Re}(\epsilon) > 0, \text{Im}(\epsilon) = 0$ ]

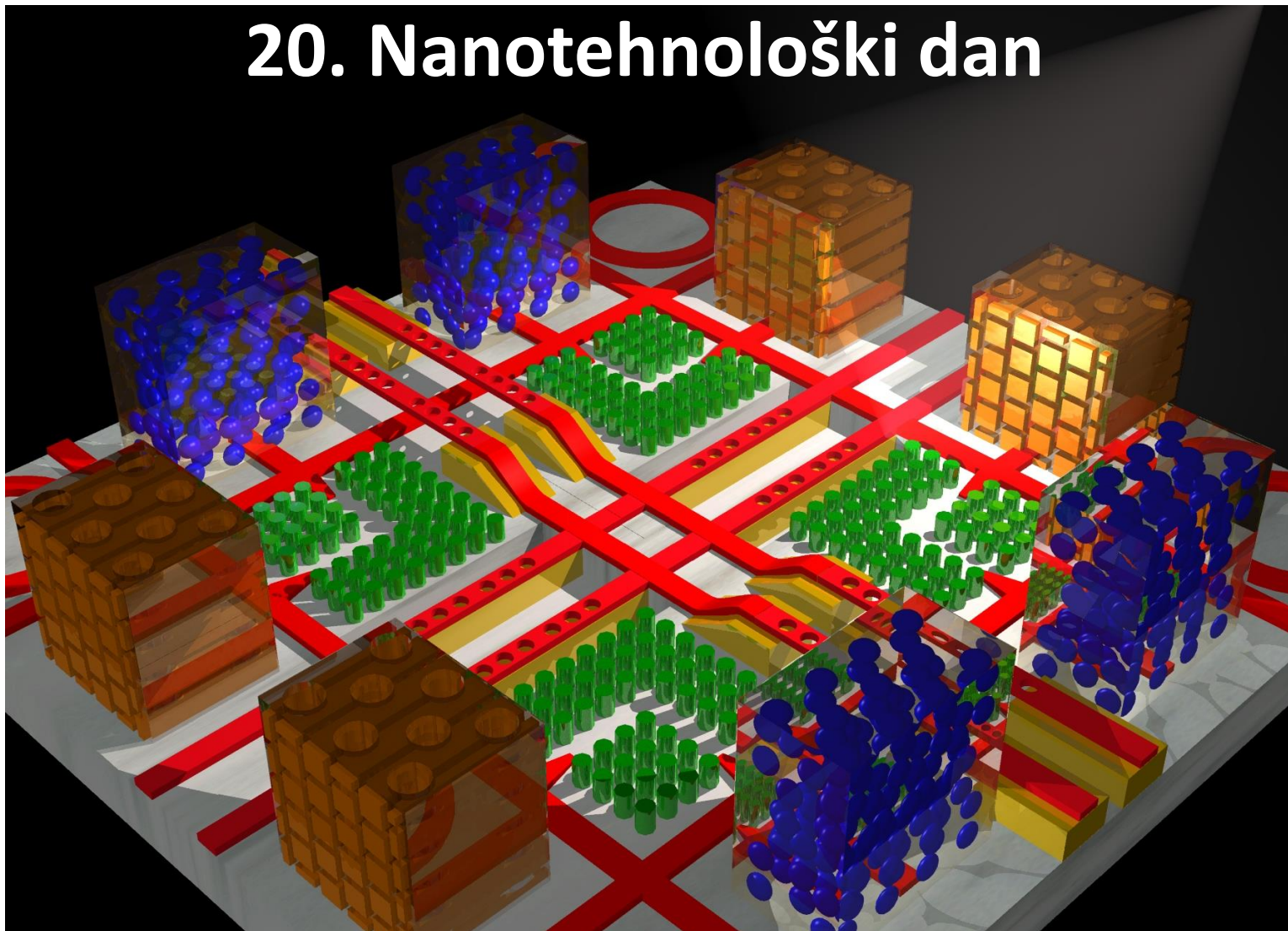
$\text{Si}_3\text{N}_4$  [ $\text{Re}(\epsilon) < 0, \text{Im}(\epsilon) \neq 0$ ]



vir: Sun, Nature Materials 11, 2012



# 20. Nanotehnoški dan



vir: MIT

Hvala za pozornost!