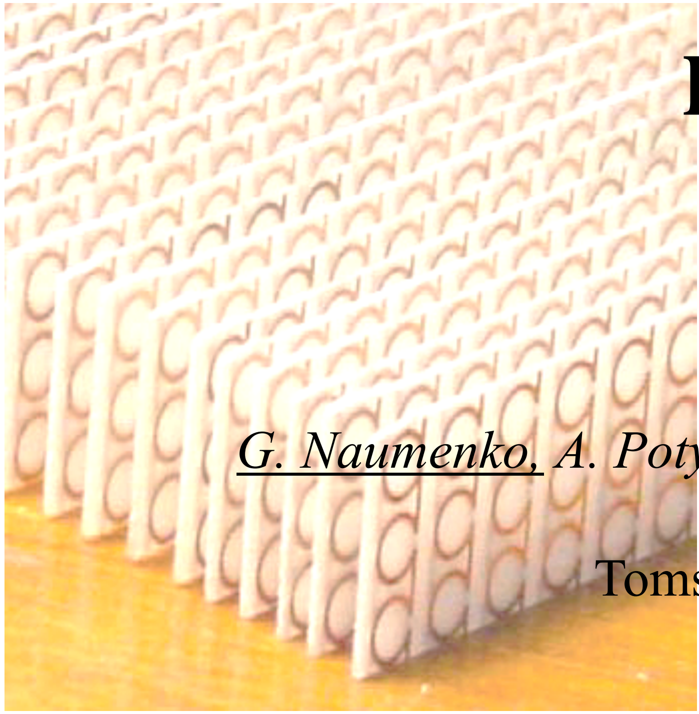
# Left-handed materials in millimetre wavelength region



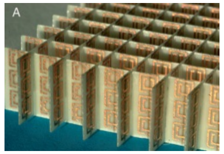
*G. Naumenko, A. Potylitsyn, M. Shevelev , V. Soboleva, V. Bleko*

Tomsk Polytechnic University

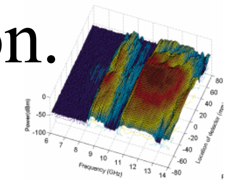
**2012**

# What about is the talk?

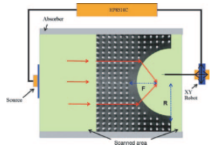
- Metamaterial properties.



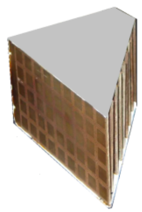

- Progress in metamaterial investigation.



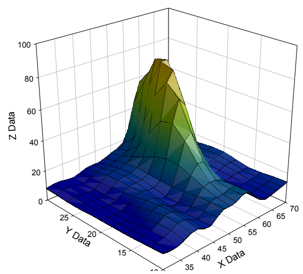
- Possible application



- Metamaterials in Tomsk Polytechnic University



- Result of investigations

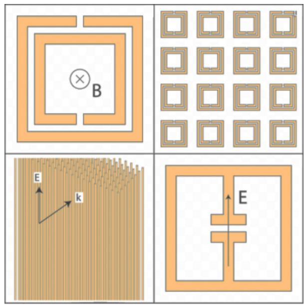


# What is metamaterial? Main properties

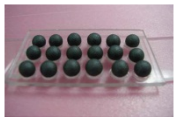
In 1968, Veselago proved the possibility of the existence of materials with negative refractive index ( $n < 0$).
(V. G. Veselago, Sov. Phys. Usp. **10**, 509 (1968))

In 1999 was shown that $n < 0$ may be realized by creation of the area of the circular resonators with gaps.
(J. B. Pendry, … IEEE Trans. Microwave Theory Tech. **47**, 2075 (1999).)

After this many different structures were suggested and tested

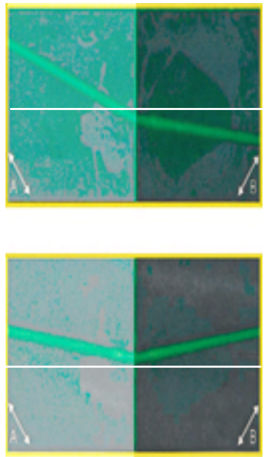






**Properties**

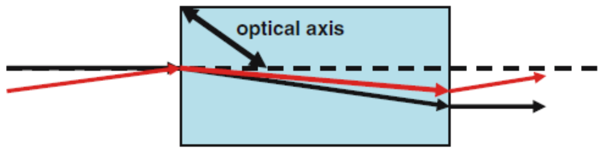
**Refraction**



$n > 0$

$n < 0$

**Focusing by flat lens**

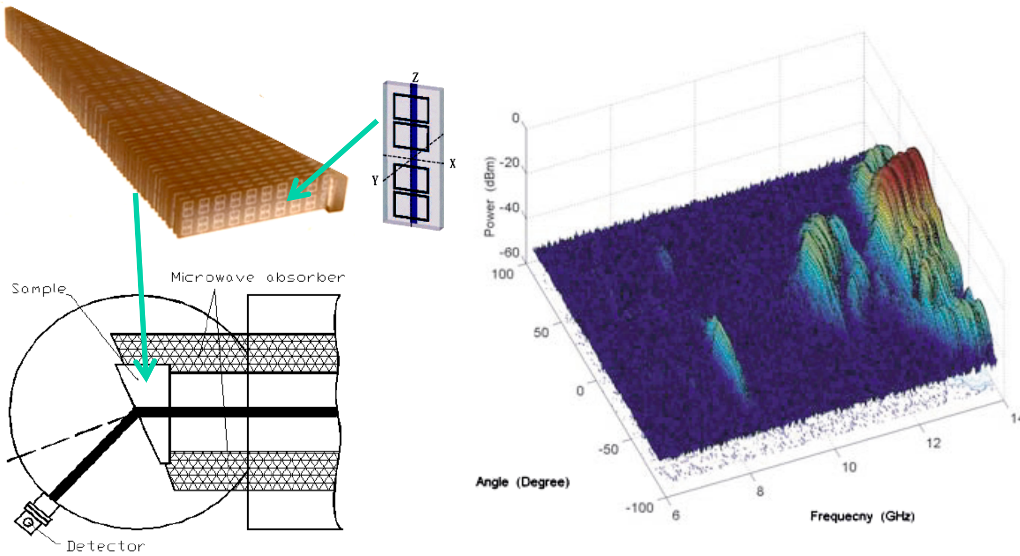


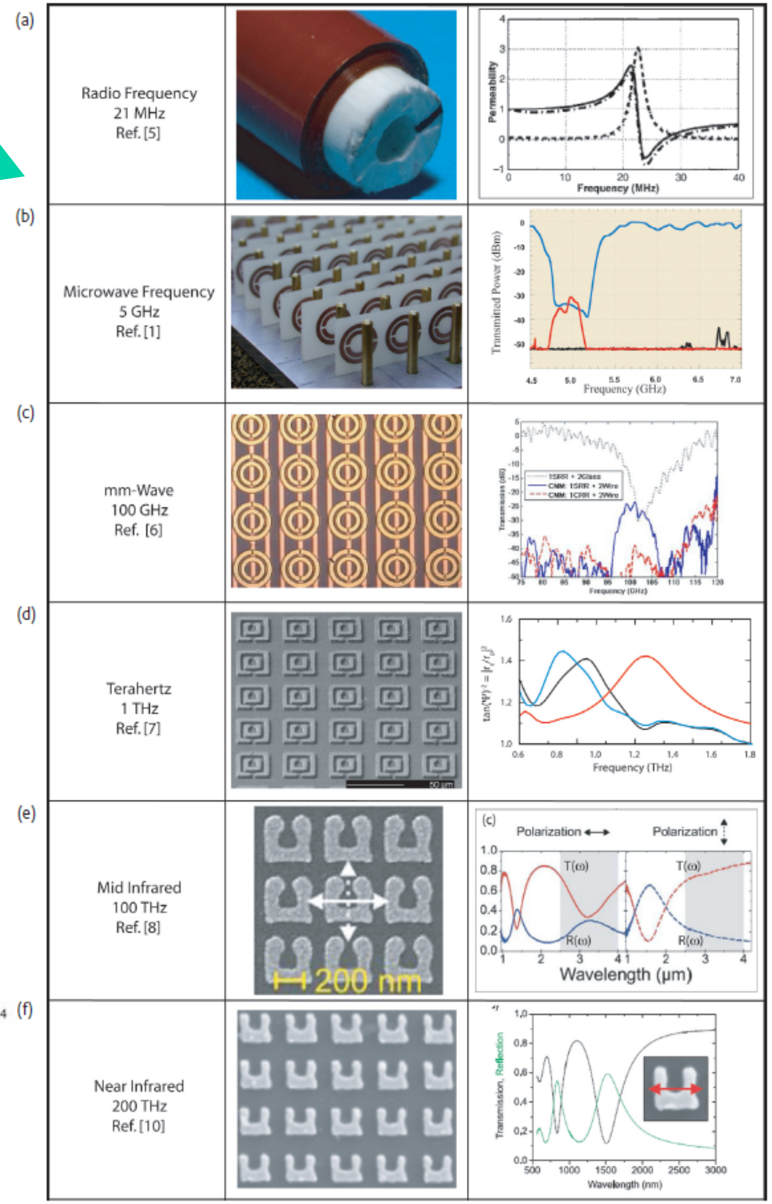
# Progress in metamaterial investigation

Since 1999 different structures from MHz to infrared spectral region were investigated, and the negative refraction index was registered.

However mainly the transmission and reflection coefficients were measured.

**More interesting measurement (spectral-angular distribution from prism) was performed by L. Ran, J. Huangfu, et.al.**
(L. Ran, J. Huangfu, et.al. Progress In Electromagnetics Research, PIER 51, 249–279, 2005)



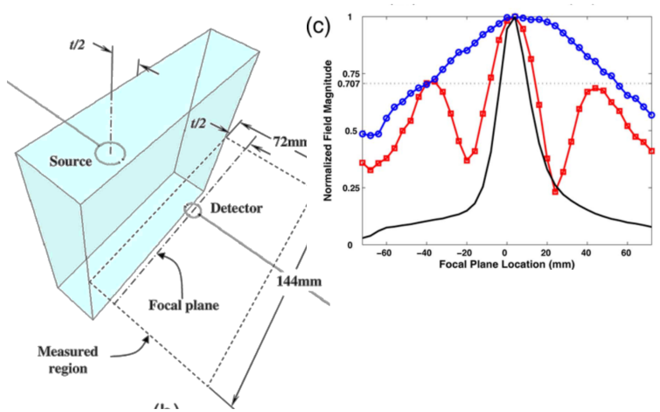



# Possible application

- Overcoming the Diffraction Limit

  Ashwin K. Iyer and George V. Eleftheriades, IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 57, NO. 6, JUNE 2009

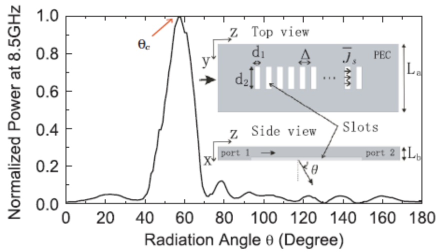
  Diffraction limit at 2.4 GHz:




- Reversed Waviolov-Cherenkov radiation

  Xi, Sheng et al. Phys. Rev. Letters 103.19 (2009)

  ***Modeling the WChR by laser beam near the grating:***




## Exotic applications

- Bypass the visibility of objects (cloak for invisibility)

  Andrea Alù. Phys. Rev. B 80, 245115 (2009)

- An electromagnetic black hole made of metamaterials.

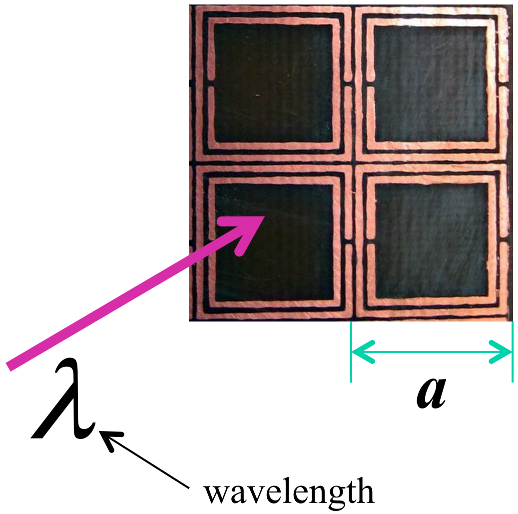
  Tom G Mackay *et al* 2005 *New J. Phys.* **7** 171

# Metamaterials in Tomsk Polytechnic University

## **Why the millimeter wavelength region?**

According to the similarity law
in case of target geometrical similarity,
all effects are defined by the relation

$$Effect = f\left(\frac{a}{\lambda}, n\right)$$

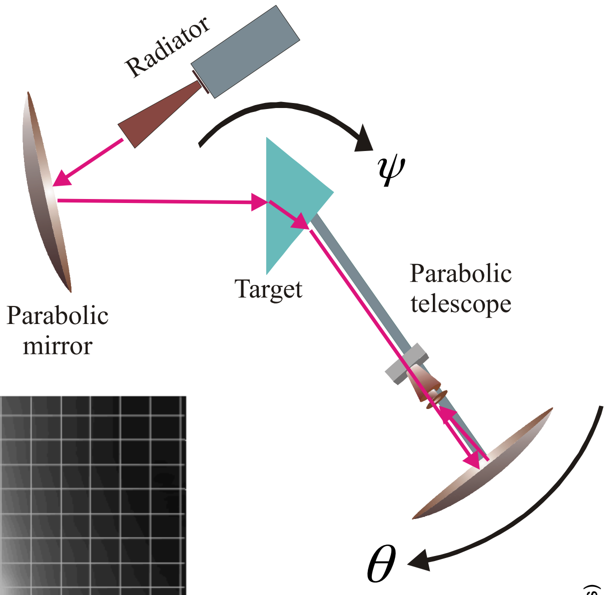


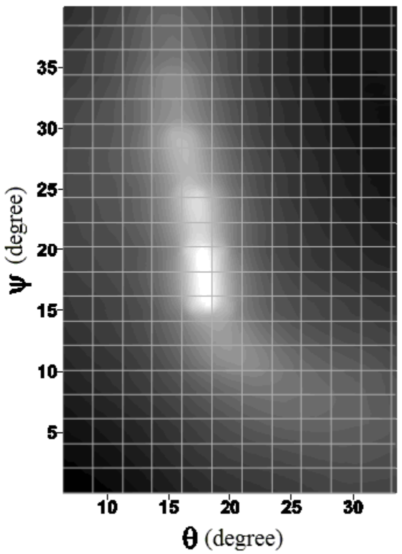

So, results obtained in mm wavelength region may be used in region from THz to MHz.

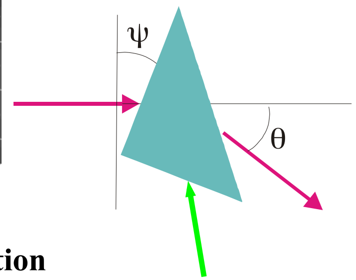
But the target production for mm wavelength region is much simply and chipper.

# Experimental technique

## Angular and orientation dependence measurement in free space.

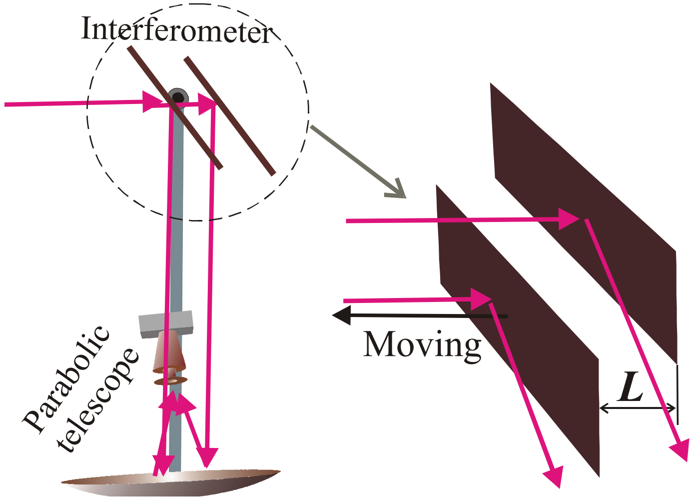


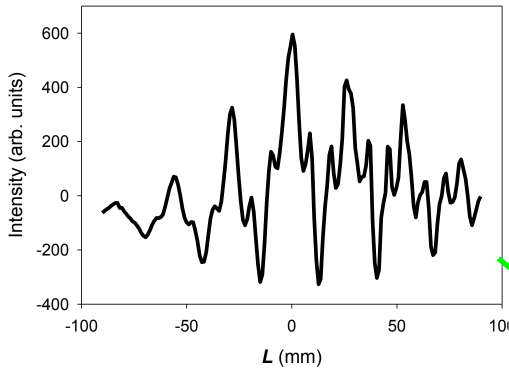




**Sample of intensity distribution of radiation from teflon target**
***n*=1.41**

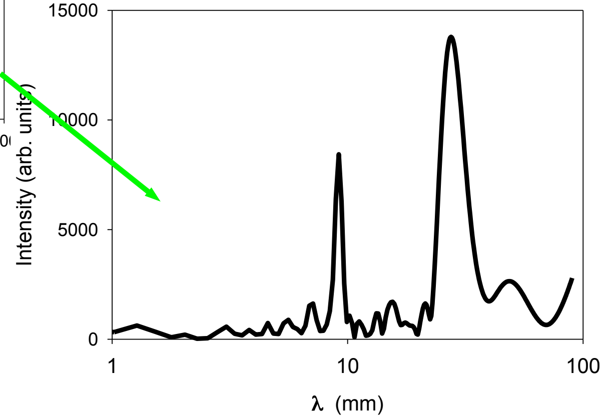
## Spectra measurement



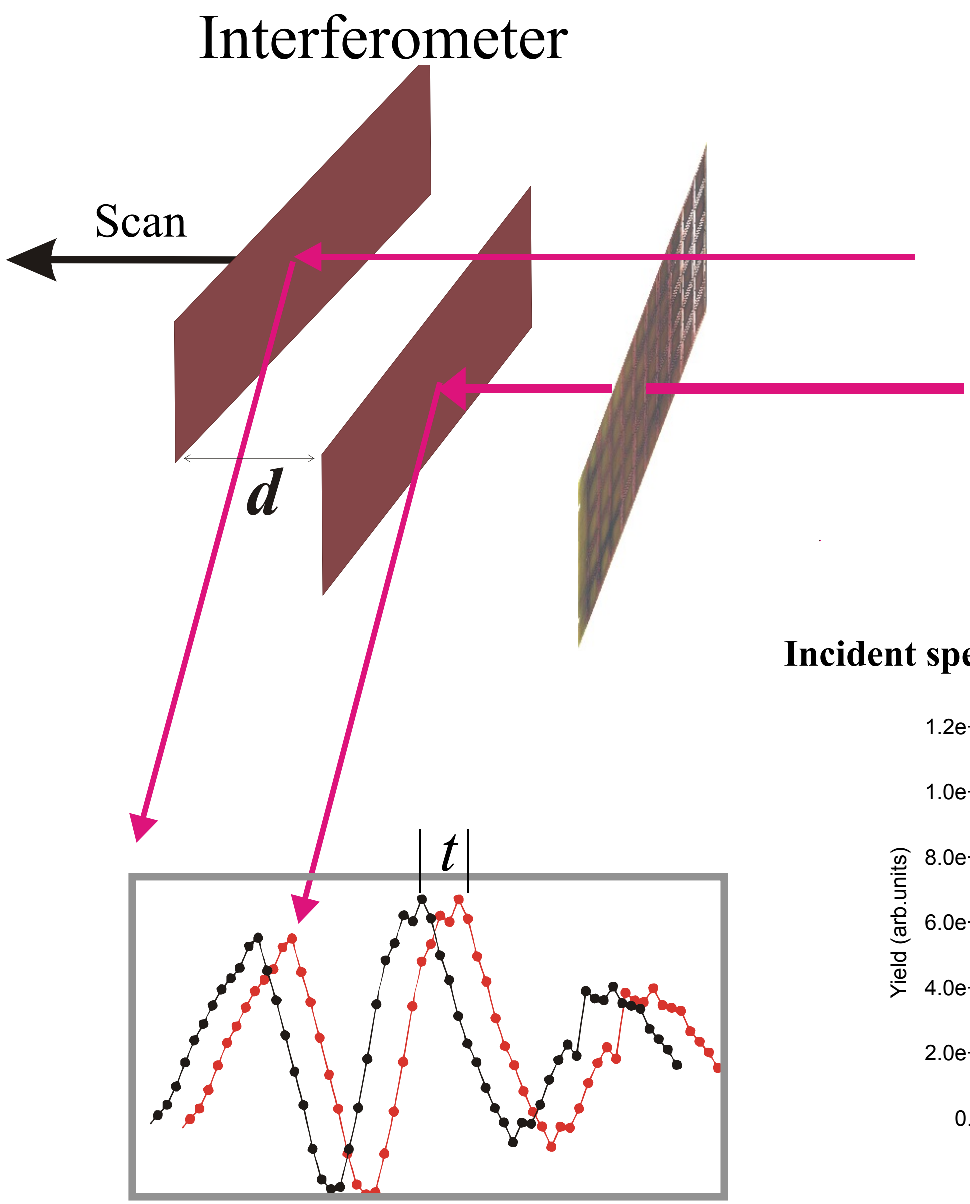




The sample of interferogram of incident radiation

The spectrum reconstructed from the interferogram

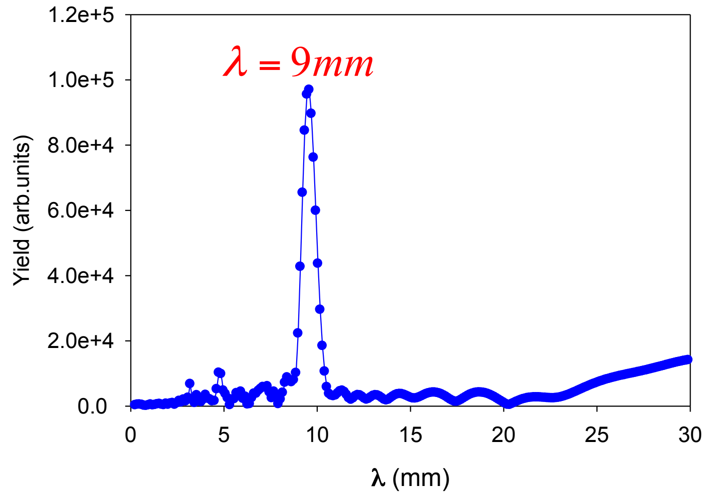


# Phase delay measurement technique.




**The main local effect of the metamaterial structure is the radiation phase delay.**

**Incident spectrum for phase delay measurement**

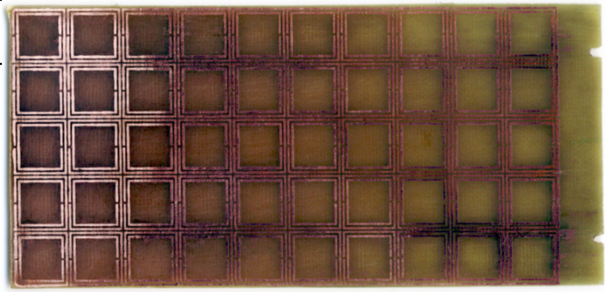


# Measurements:

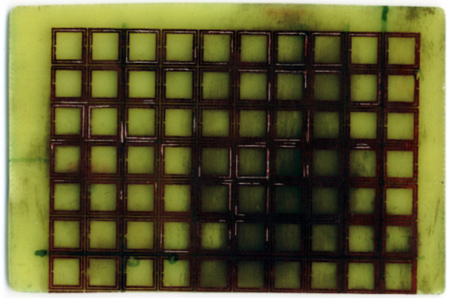
## Phase delay

Structures used

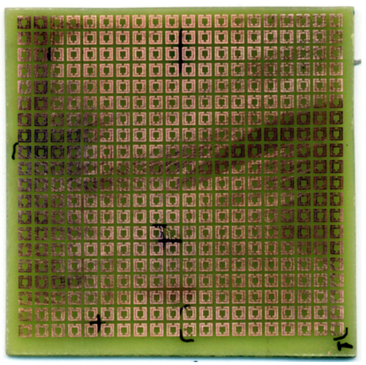
*a*



***a* = 12 mm.**



***a* = 8.5 mm.**



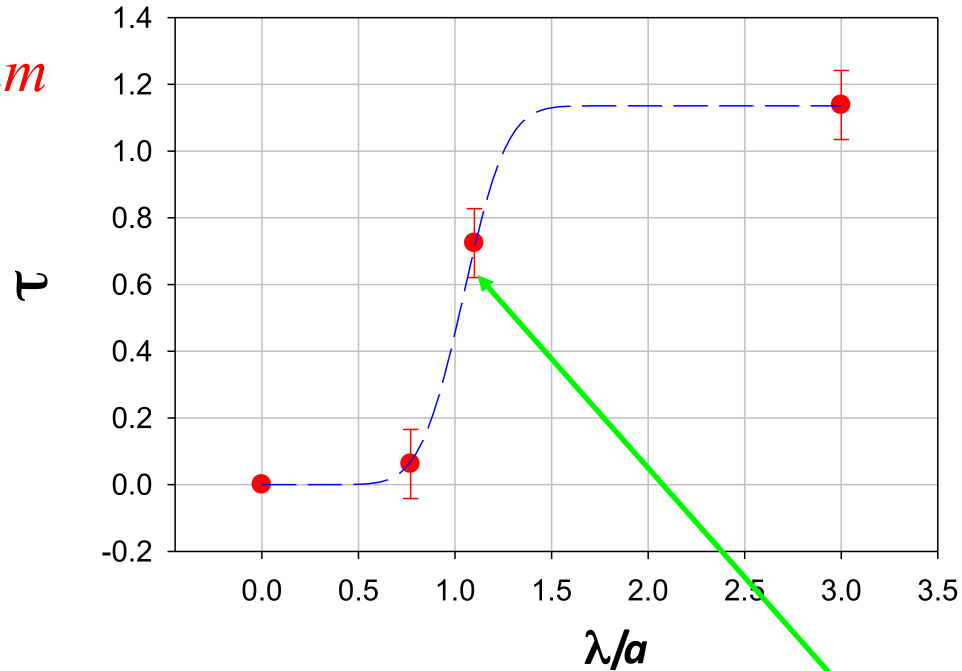
***a* = 3 mm.**

$\lambda = 9mm$

The phase delay in substrate from glass fiber of thickness 1.5 mm was measured and subtracted.

$\tau = 2\pi/\lambda * (t - t_{substr})$

$t_{substr} = 2.1mm$

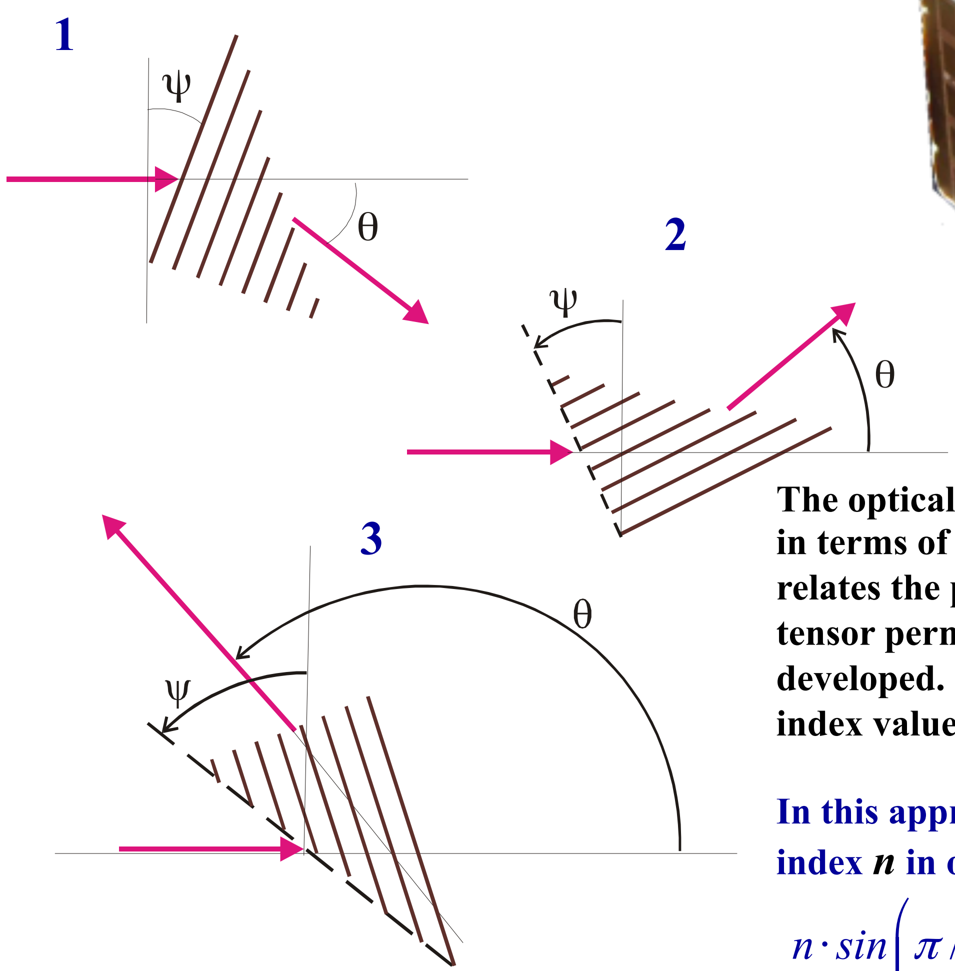



*The main structure effect appears for* $\lambda / a \approx 1$

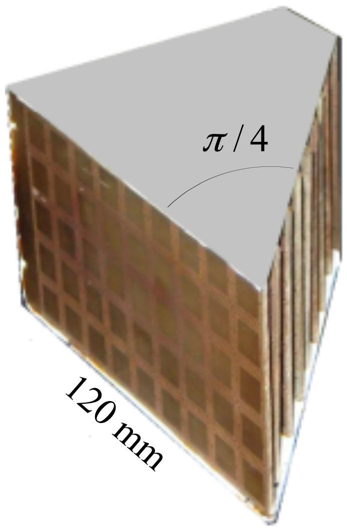
$a$ = 12 mm for prism target was chosen

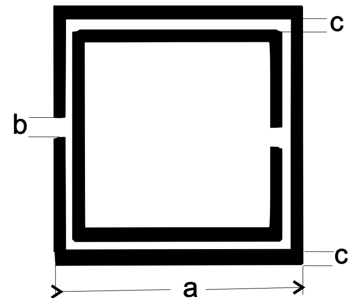
# Refractoin in metamaterial

## Geometry investigated




## Target




**Unit cell**

c = b = 0.05*a*, ***a*=12 mm**

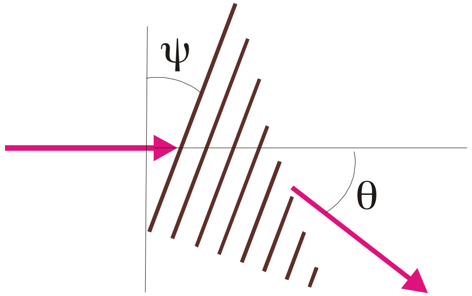
**The optical properties of metamaterials should be considered in terms of tensor integral parameters. However, a theory that relates the parameters of the structures of metamaterials with tensor permittivity and permeability, has not properly developed. Therefore the scalar approach of the refraction index value is used in many articles.**

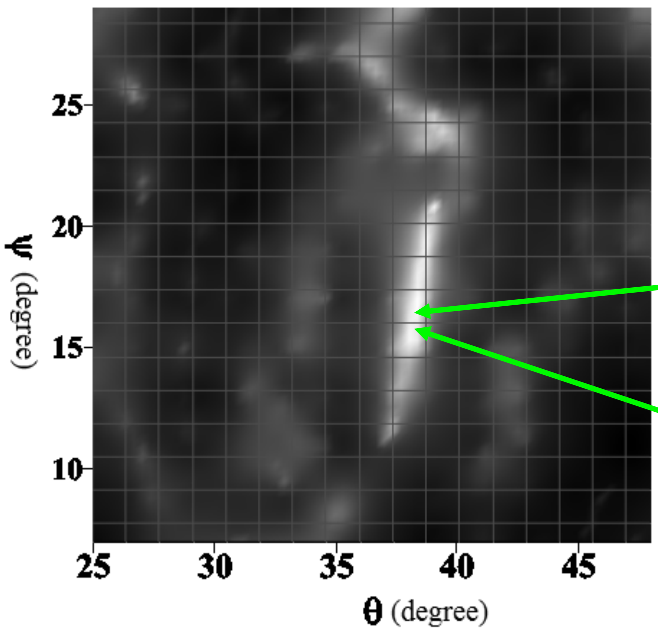
**In this approach, according the Snellius law, the refractive index *n* in our coordinate system may be found from equation:**

$$n \cdot \sin\left(\pi/4 - \arcsin\left(\frac{\sin\psi}{n}\right)\right) = \sin\left(\theta + \pi/4 - \psi\right)$$

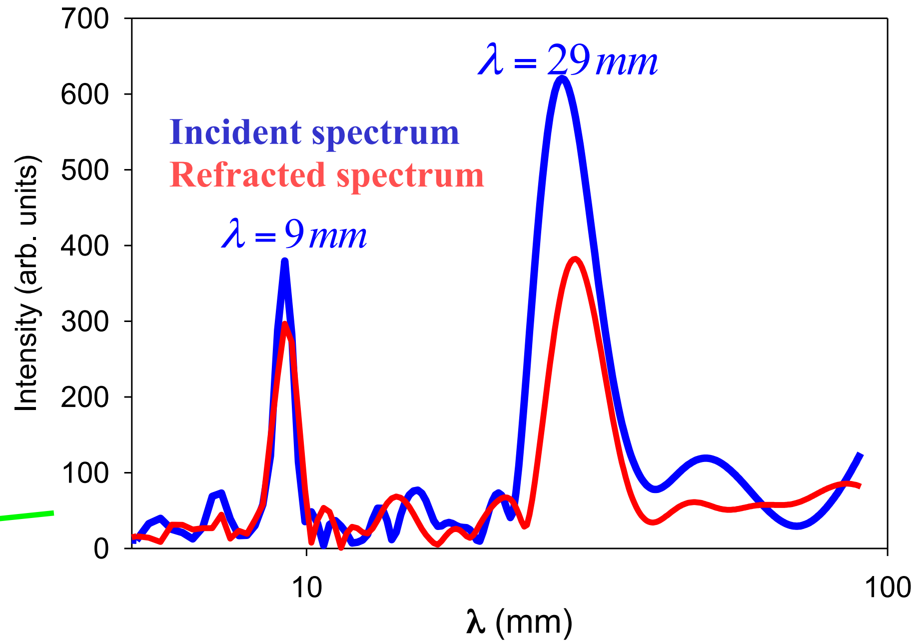
# Refraction measurements

## Geometry 1



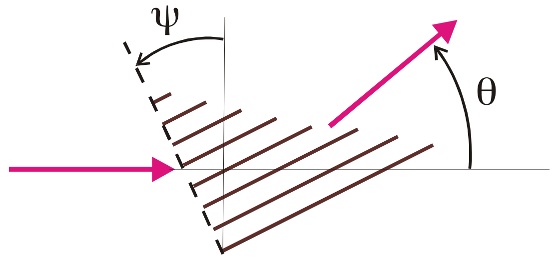

Distribution of radiation intensity in the plane of observation angle $\theta$ and orientation angle $\psi$

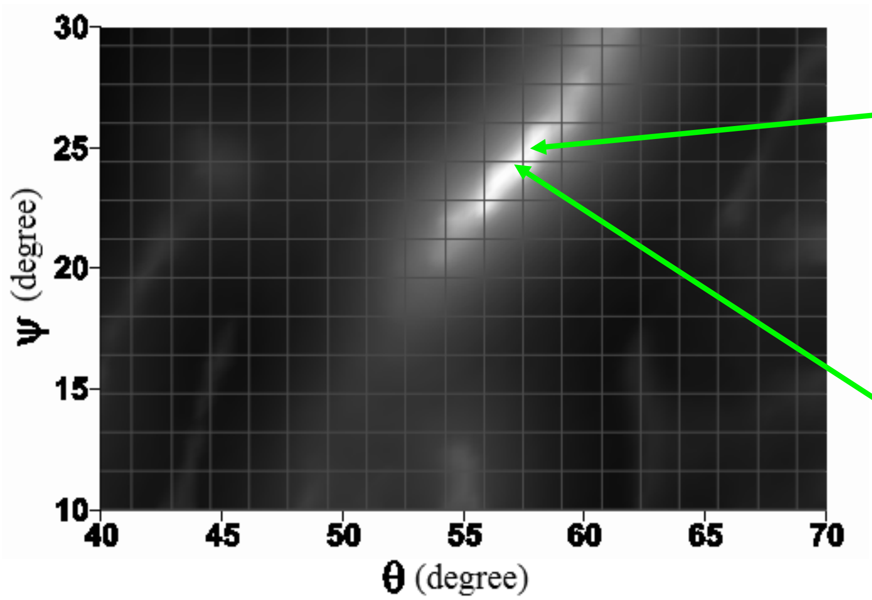


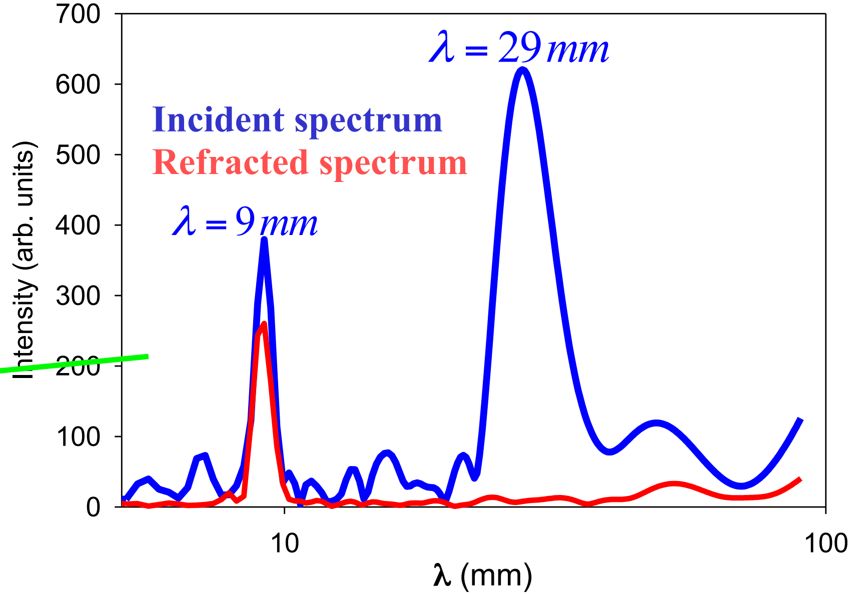

$$n = 1.64$$

**Usual refraction**

# Geometry 2



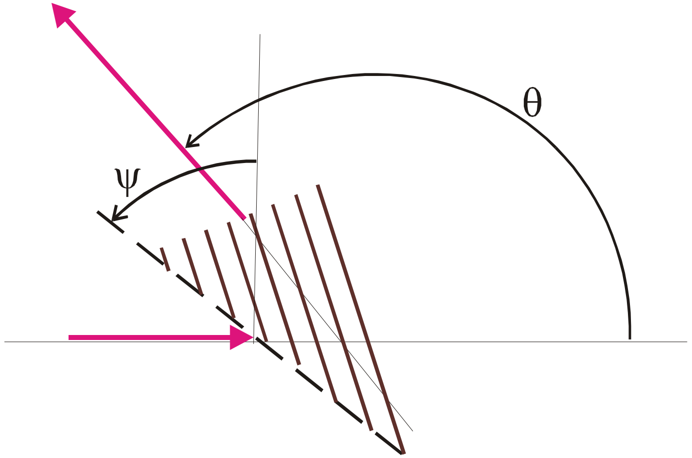

**n = - 0.5**

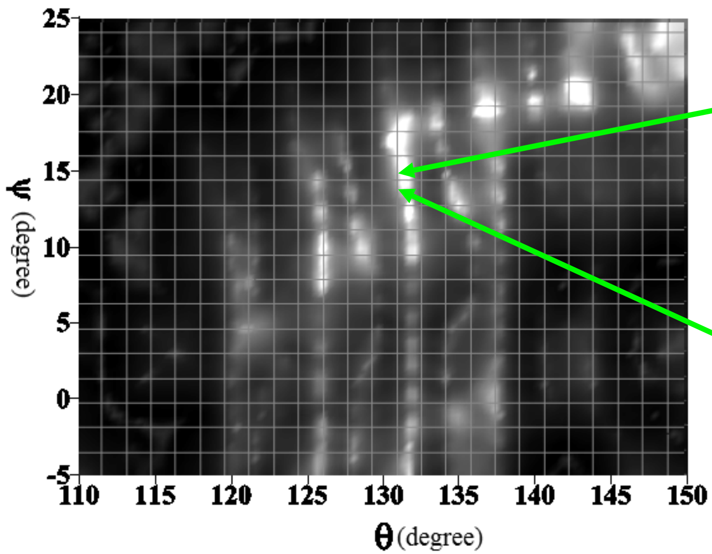
$\lambda < a$

Distribution of radiation intensity in the plane of observation angle $\theta$ and orientation angle $\psi$

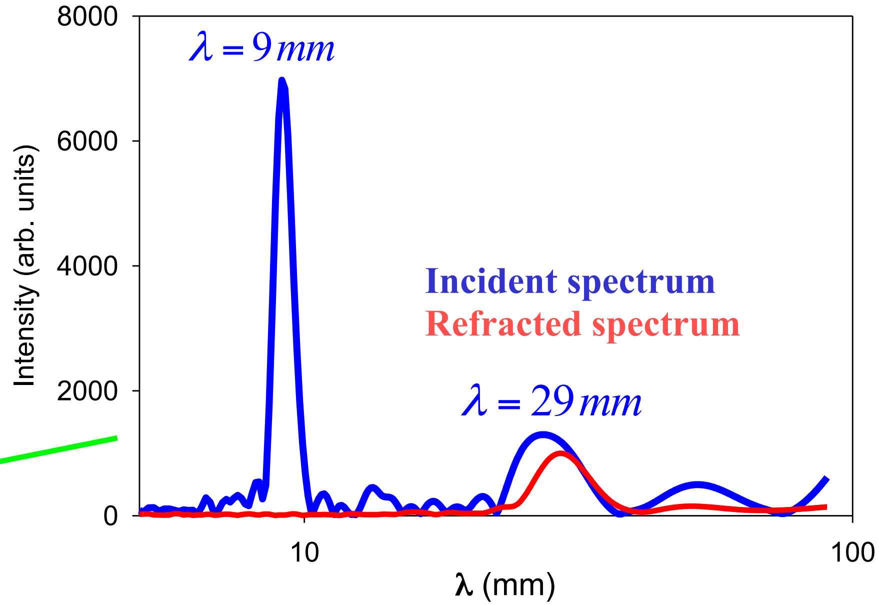
**Refraction with negative refraction index (not a reflection)**

# Geometry 3




Distribution of radiation intensity in the plane of observation angle $\theta$ and orientation angle $\psi$




$\lambda > a$

**n = - 1.45**

**Backward refraction**

# Summery

- **Analysis of the experimental results shows that the behavior of the radiation in the metamaterials is complex.**
- **The main structure effect appears for** $\lambda / a \approx 1$
- **In the refractive index scalar approach, its value in different refractive geometry may be either positive or negative, up to the backward refraction.**
- **A theory that relates the parameters of the structures of metamaterials with tensor permittivity and permeability, has not properly developed.**

Thank you for your attention