Design of sensing elements for the mid-IR spectroscopy on the base of electromagnetic theory of optical fibers

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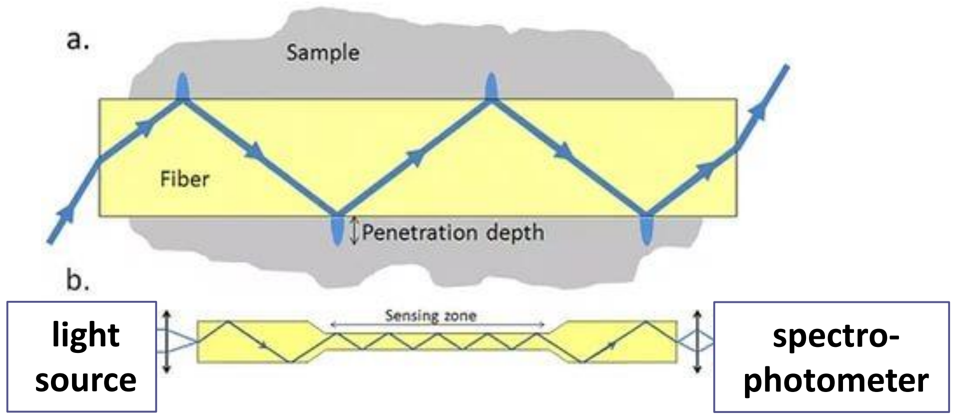
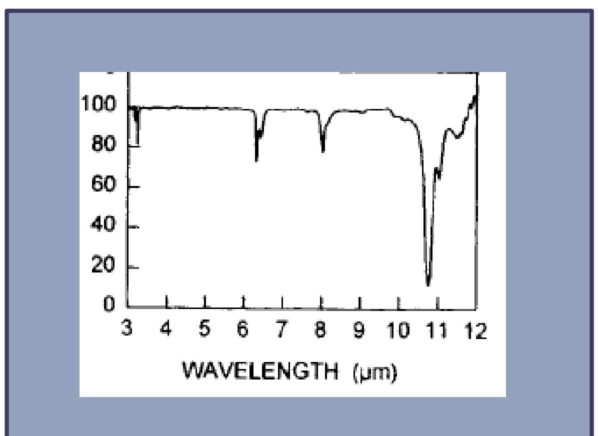
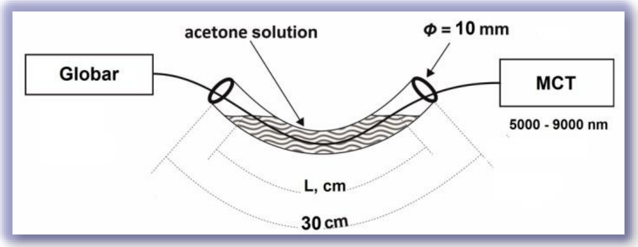
Evanescent wave absorption spectroscopy:
the Method



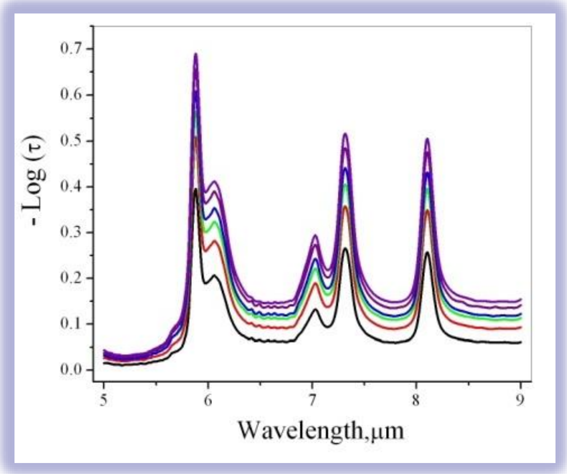
Transmittance



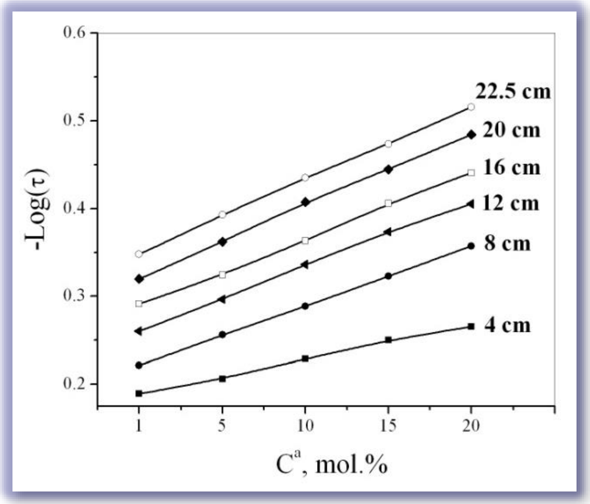
Evanescent wave absorption spectroscopy:
Measurements



Acetone aqueous solution
C^a = 1%, 5%,10%, 15%, 20%



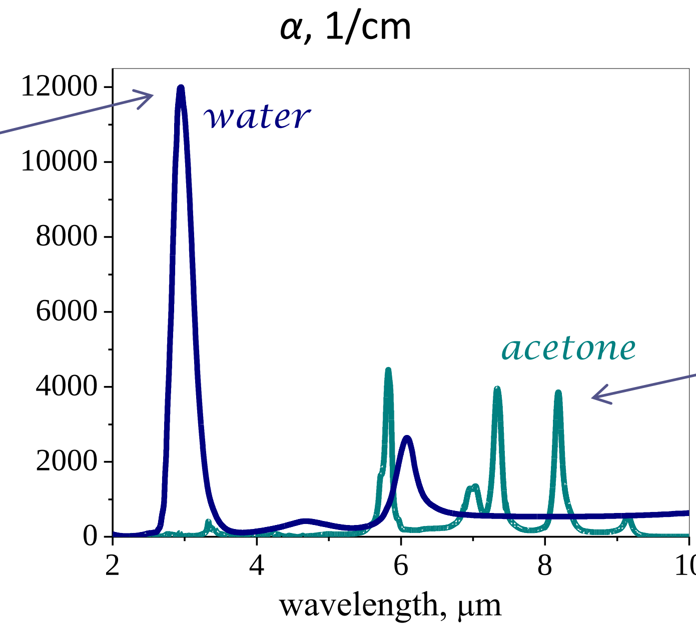
- Log (T)



Absorption of liquids in the mid-IR

$L_a = 1\ \mu m$

$L_a = 1/\alpha$



$L_a = 3\ \mu m$

Spectroscopy of liquids

Outline

1. Evanescent modes of an optical fiber

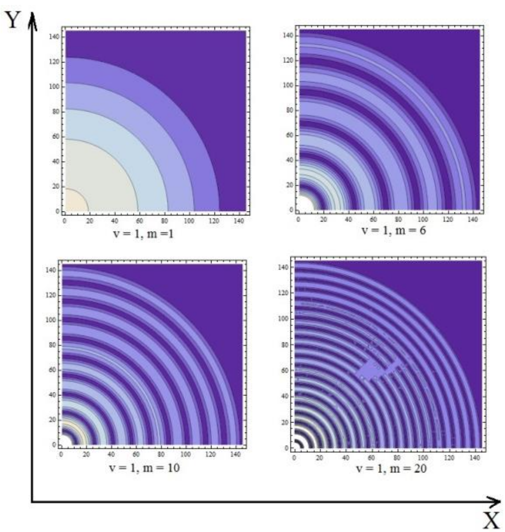
2. Peculiarities of the evanescent wave sensing in mid-IR by using multimode optical fibres

3. Design an optimization of the sensing elements based on multimode optical fibres

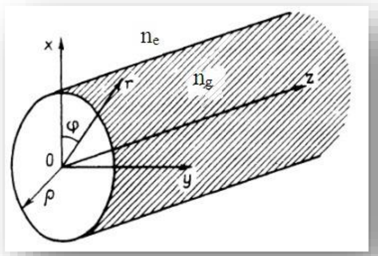
4. Conclusions

Evanescent modes

Optical fibre immersed in an analyte =
dielectric cylindrical waveguide with an absorbing cladding



HE$_{1m}$ - modes



$$n_g = n_g^{'} + i \cdot n_g^{''}$$

$$n_e = n_e^{'} + i \cdot n_e^{''}$$

1. $\beta = \beta' + i\,\beta''$
2. $S_r \neq 0, \quad S_\varphi \neq 0$

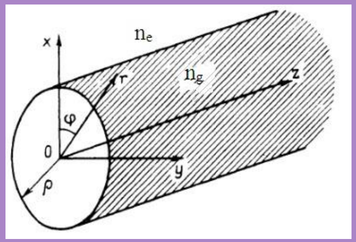
$$S_z(z) = S_z(0) \cdot e^{-2\cdot\beta'' z}$$

$$T(L) = e^{-2\cdot\beta'' L}$$

Evanescent modes

Characteristic equation for the HE_{1m} modes:

$$\left\{\frac{J_v'(U)}{U\cdot J_v(U)}+\frac{K_v'(W)}{W\cdot K_v(W)}\right\}\cdot\left\{\frac{J_v'(U)}{U\cdot J_v(U)}+\frac{n_{cl}^2}{n_{co}^2}\cdot\frac{K_v'(W)}{W\cdot K_v(W)}\right\}=\left(\frac{v\cdot\beta}{k\cdot n_{co}}\right)^2\cdot\left(\frac{V}{U\cdot W}\right)^4$$



$$n_{cl}=n_{cl}'+i\cdot n_{cl}''\qquad n_{cl}''=\left(\alpha_m^w c^w+\alpha_m^a c^a\right)\cdot\ln(10)/(2k).$$

$\alpha_m{}^w$ - molar absorption coefficient of water, cm^{-1}

$\alpha_m{}^a$ - molar absorption coefficient of acetone, cm^{-1}

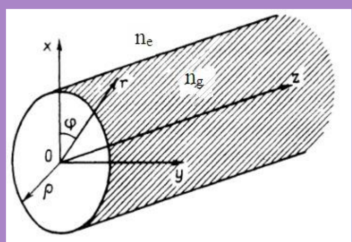
C^w - concentration of water,

C^a - concentration of acetone

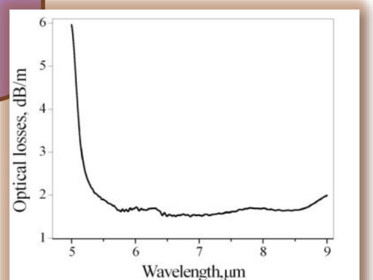
$$\beta_m''$$

$$T=\frac{\sum_m S_z^{1m}(L)}{\sum_m S_z^{1m}(0)}$$

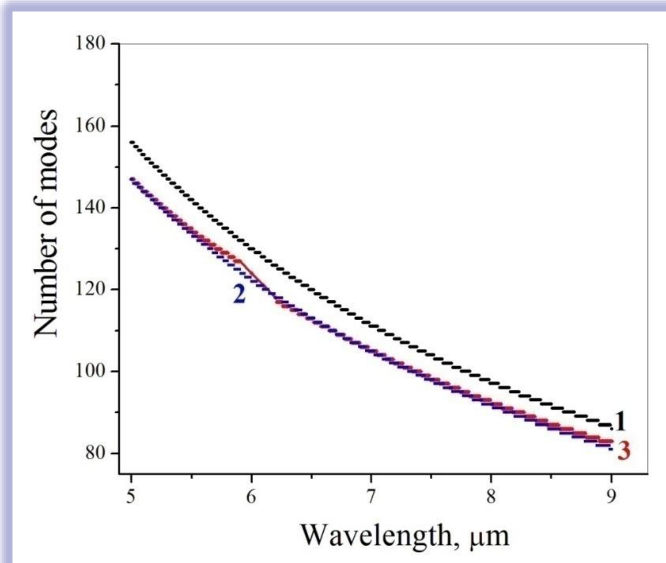
Evanescent modes



$[Ge_{26}As_{17}Se_{25}Te_{32}]$:
ρ = 300 µm;
n = 2.8



Number of the HE_{1m} evanescent modes



Fiber immersed
1 in the air,
2 in the water (n=1.33) or
acetone (n=1.35)

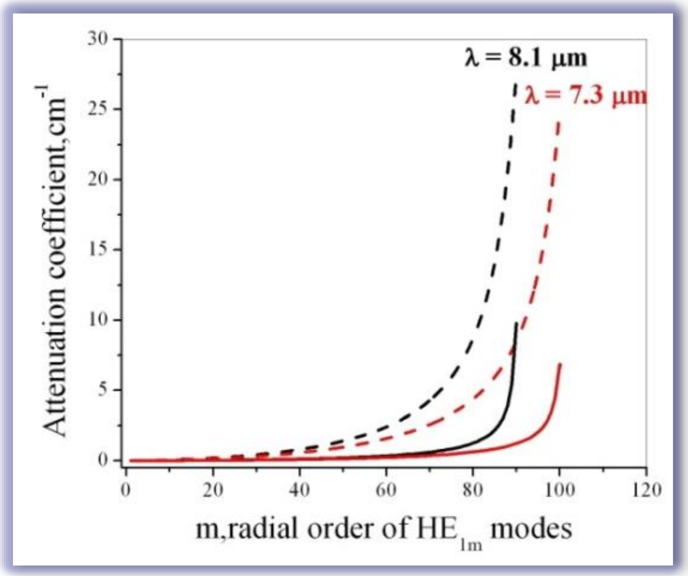
Peculiarities:

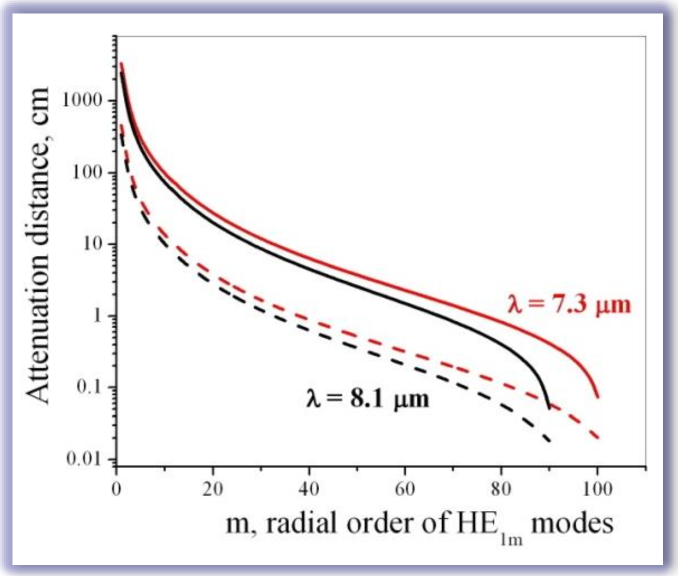
- Attenuation coefficients of the evanescent modes grow with their radial order
- Attenuation distances of the evanescent modes decrease with their radial order

$[Ge_{26}As_{17}Se_{25}Te_{32}]$:
ρ = 300 µm;
n = 2.8

$$\eta_m = 2 \cdot \beta''$$

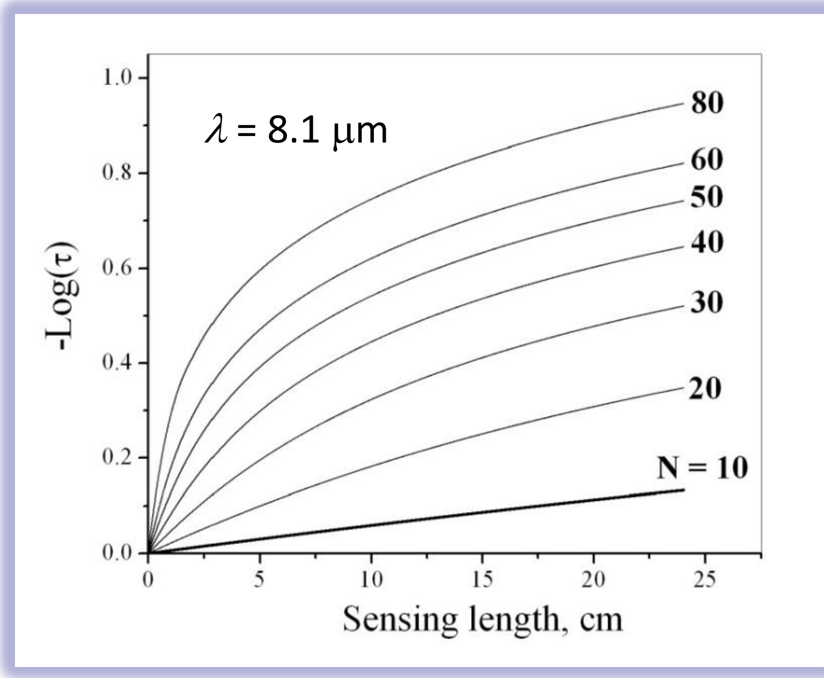
$$L_m = \frac{1}{\eta_m}$$

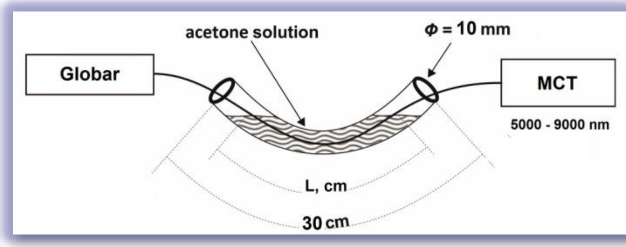


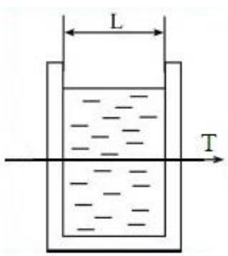


Peculiarities:

- in a multimode fiber, -Log(*T*) is not linearly proportional to *L*





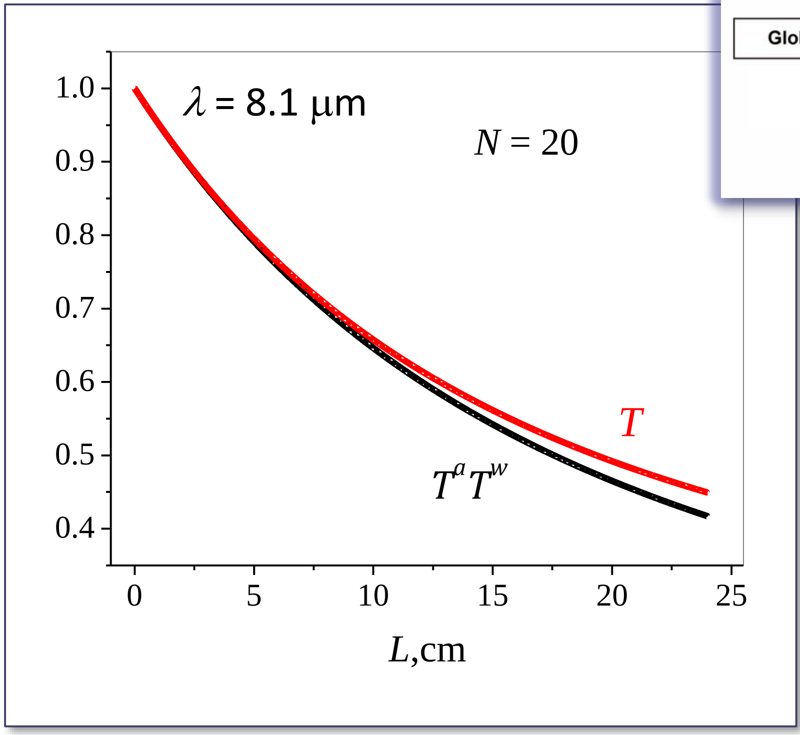


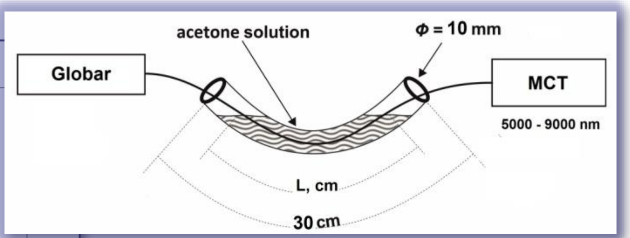
- in measurements with bulk substances:

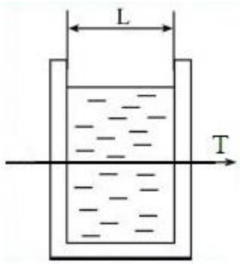
$$A = (\alpha_m^w \cdot c^w + \alpha_m^a \cdot c^a) \cdot L = -\log(T)$$

Peculiarities:

- total transmittance of a fiber immersed into a solution is not equal to the product of transmittances of the solution components







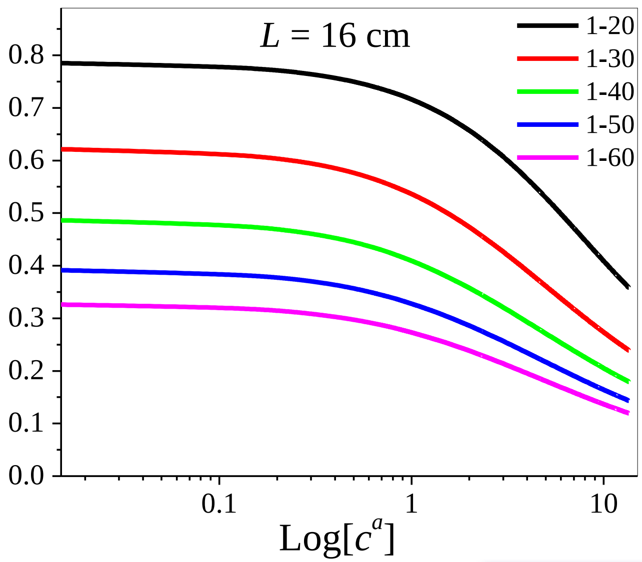
- in measurements with bulk substances:

$$T = 10^{-(\alpha_m^w \cdot c^w + \alpha_m^a \cdot c^a)\cdot L} = T^w \cdot T^a$$

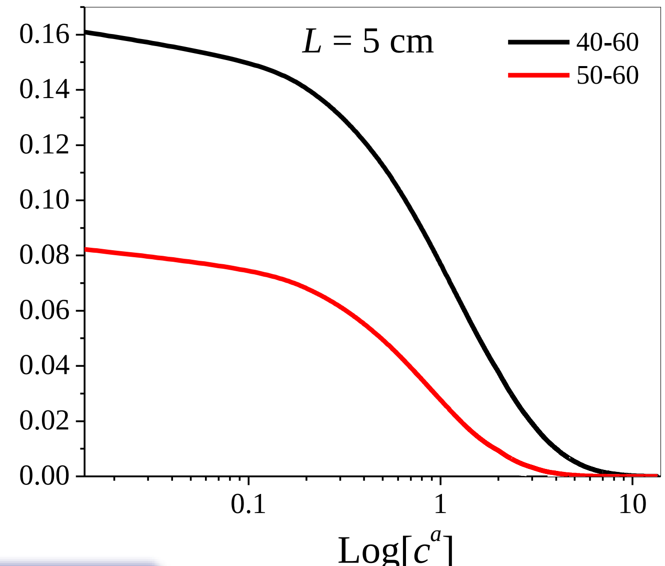
Peculiarities:

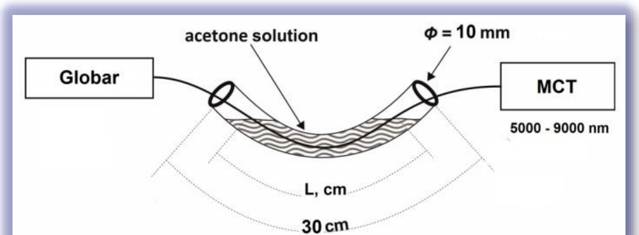
- calibration curves depend on the number and sampling of propagating evanescent modes

$$T = \frac{\sum_m S_z^{1m}(L)}{\sum_m S_z^{1m}(0)}$$



λ = 8.1 μm





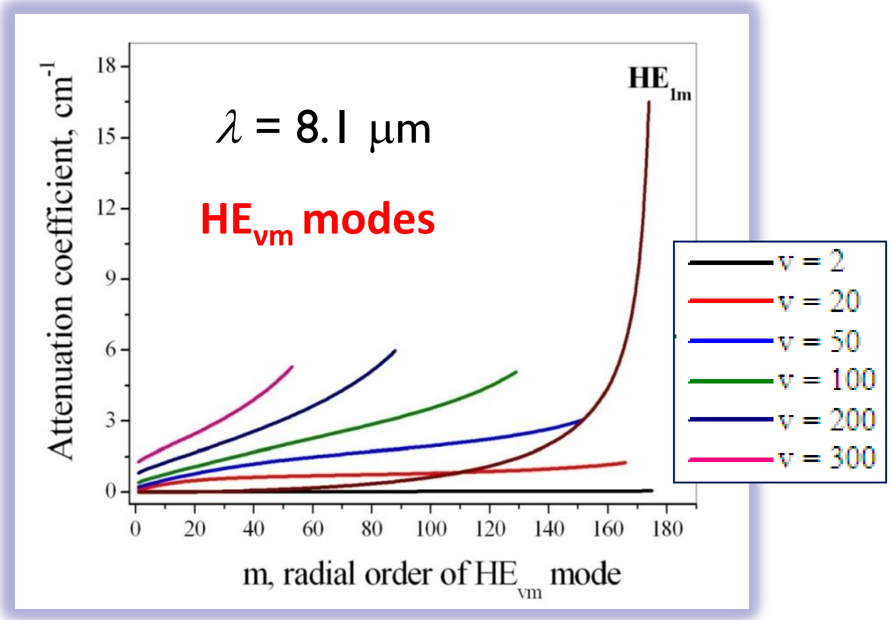
Design:

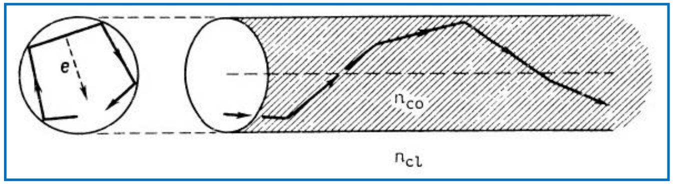
- to increase the attenuation coefficient

1. To decrease the fibre diameter

2. To work at longer wavelengths

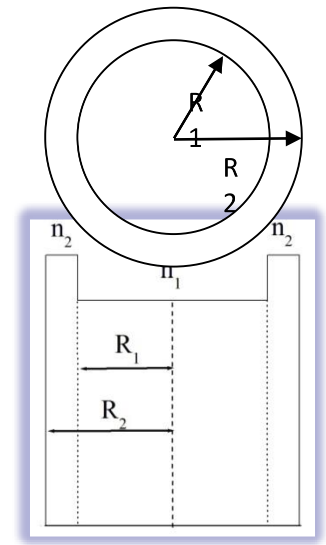
3. To use tilted rays





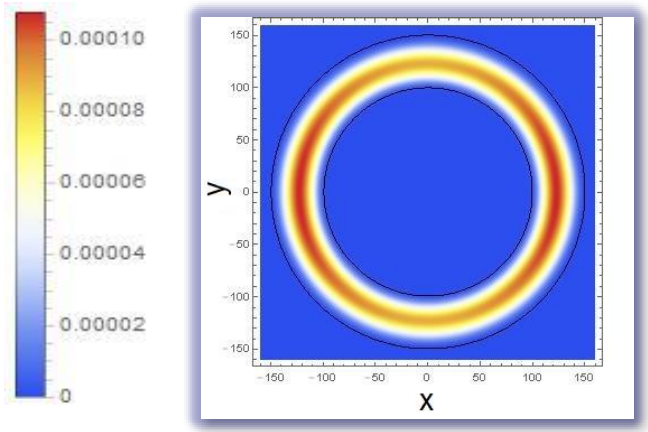
Design:

- to increase the attenuation coefficient



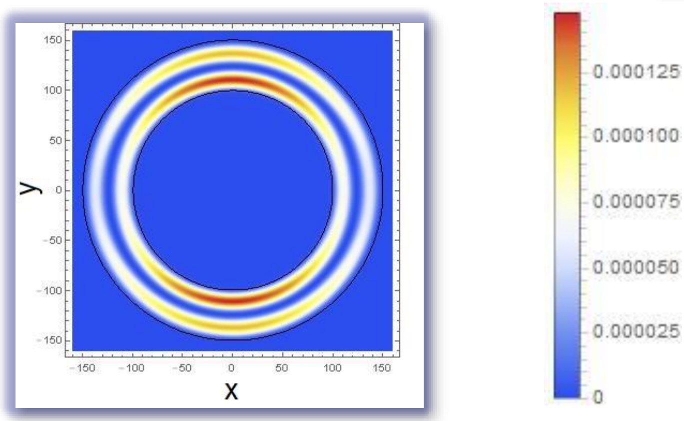
4. To manage the refractive index profile

Intensity



HE$_{11}$ mode

Intensity

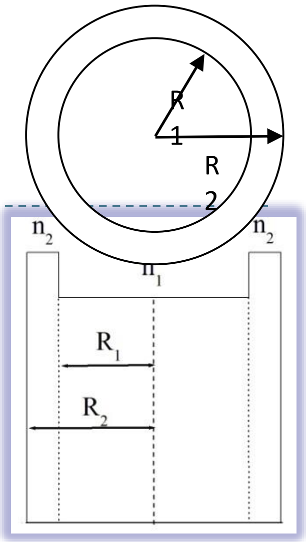


HE$_{12}$ mode

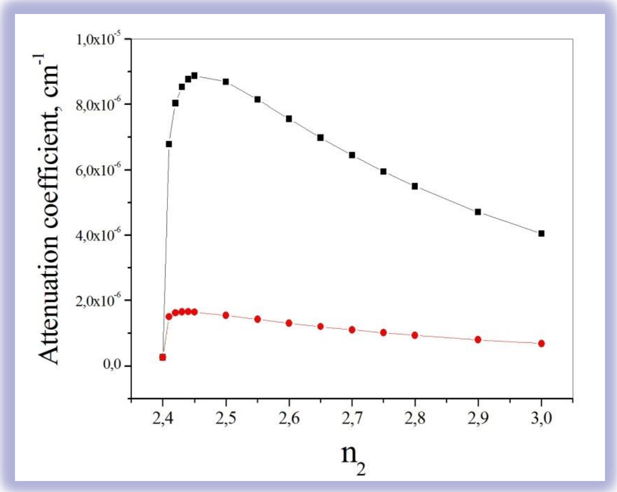
A. G. Rozhnev, «Stable Method for the Calculation of Layered Dielectric and Metal–Dielectric Waveguide Structures with Circular Cross Sections», TECHNICAL PHYSICS LETTERS, Vol. 35, No. 3, 2009

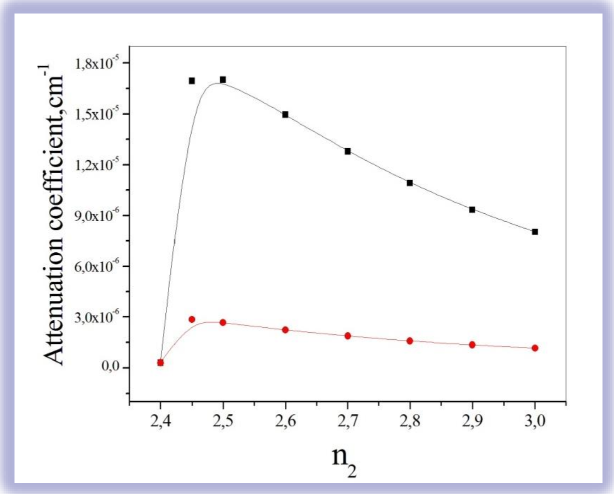
Design:

- to increase the attenuation coefficient



Attenuation coefficient of the HE_{1m} modes





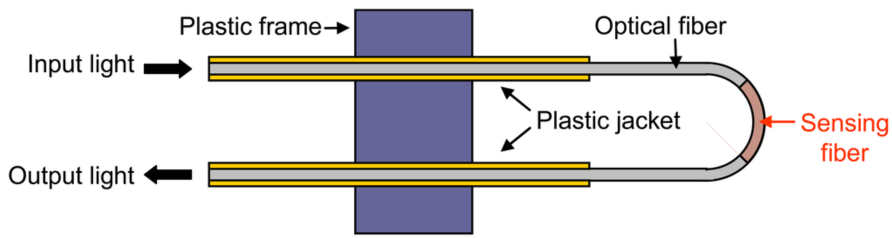
HE_{11} mode

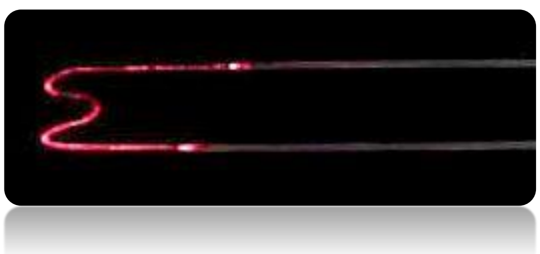
λ = 8.1 μm

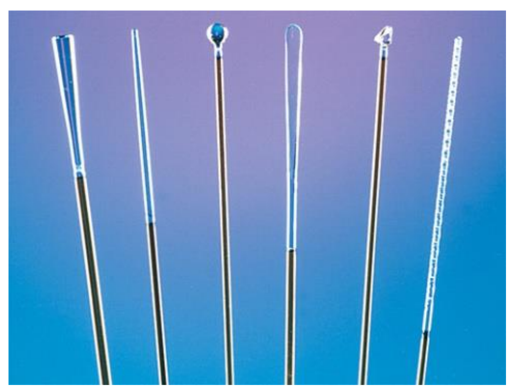
HE_{12} mode

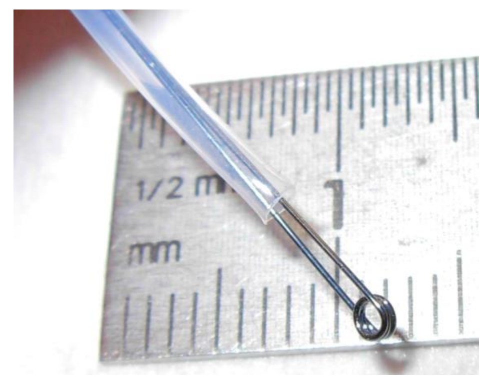
$\Delta R = 10$ μm
$\Delta R = 20$ μm
$R_2 = 60$ μm

Design:
- selective excitation and mixing of the evanescent modes









References

1. E.A. Romanova, S. Korsakova, M. Komanec, T. Nemecek, A. Velmuzhov, M. Sukhanov, V. S. Shiryaev. «Multimode chalcogenide fibers for evanescent wave sensing in the mid-IR», ***IEEE Journal of Selected Topics in Quantum Electronics,*** V.23,2, pp.1-7, 2017, doi:10.1109/JSTQE.2016.2630846.

2. S. Korsakova, E. Romanova, A. Velmuzhov, T. Kotereva, M. Sukhanov, V. Shiryaev. «Peculiarities of the Mid-Infrared Evanescent Wave Spectroscopy Based on Multimode Chalcogenide Fibers», ***Journal of Non-Crystalline Solids***, 2017, doi:10.1016/j.jnoncrysol.2017.08.027

Conclusions

-By using the approach based on the electromagnetic theory of optical fibers, some specific features of the fiber-based evanescent wave spectroscopy in the mid-IR have been revealed.

-These specific features are due to the evanescent modes of a multimode fiber have different attenuation coefficients.

- For optimization of the fiber sensor, the higher-order modes are to be excited selectively at the fiber input facet or at the fiber discontinuities.

-Methods of spectrum processing used in spectroscopy of bulk samples are not suitable in the case of the fiber-based spectroscopy.