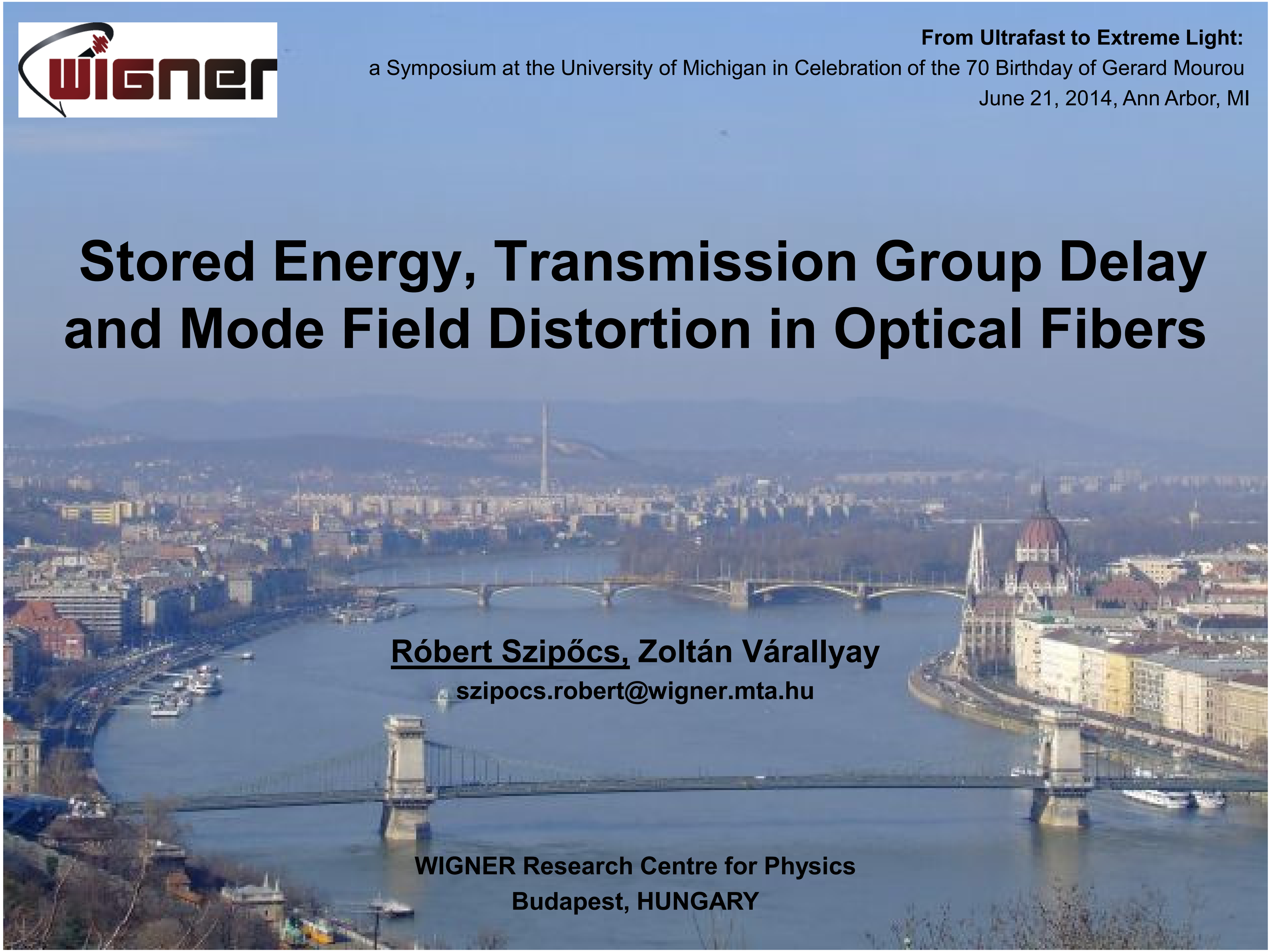

**From Ultrafast to Extreme Light:**
a Symposium at the University of Michigan in Celebration of the 70 Birthday of Gerard Mourou
June 21, 2014, Ann Arbor, MI

# Stored Energy, Transmission Group Delay and Mode Field Distortion in Optical Fibers

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**szipocs.robert@wigner.mta.hu**

**WIGNER Research Centre for Physics**
**Budapest, HUNGARY**

# OUTLINE

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- ☐ **Tunneling of optical pulses through 1D photonic bandgaps (PBG) and some other interesting phenomena to be understood**

- ☐ **Poynting’s theorem (contiunity of energy flow)**

  → Relation between reflected/transmitted group delay and energy storage in 1D PBG structures (Winful)

- ☐ **Relation between group delay, energy storage and absorbed/scattered power in <u>highly reflective dispersive dielectric mirror coatings</u>: the 1D case**

- ☐ **Energy, transmission group delay and mode field distortion in <u>optical fibers</u>: the 2D case**

# INVENTING CHIRPED MIRRORS IN 1993 (Wigner RCP / TU Wien)
# THE SOLUTION FOR ULTRAFAST SOLID STATE LASERS

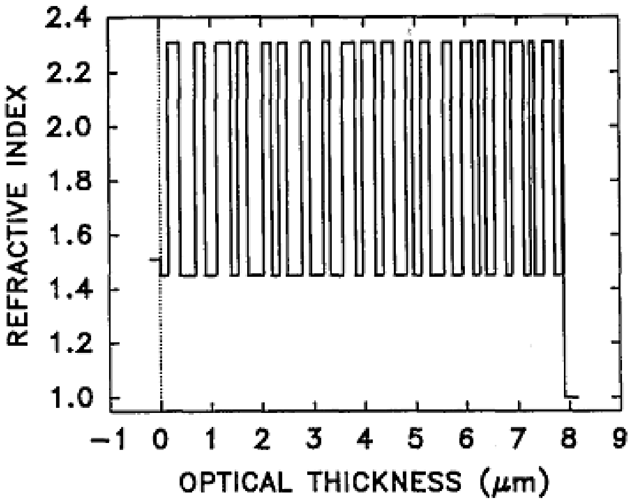


Fig. 1. Theoretical refractive-index profile of a high-reflectivity $TiO_2$–$SiO_2$ multilayer coating designed specifically for broadband GDD control in femtosecond lasers.

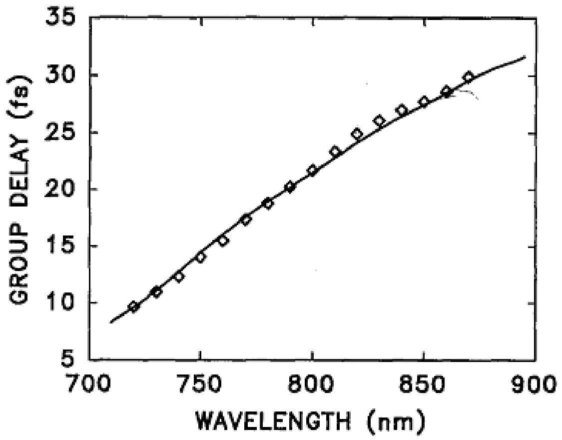
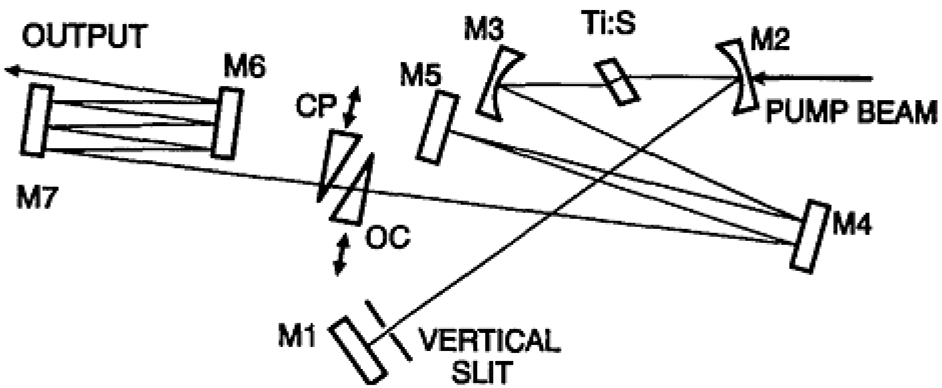


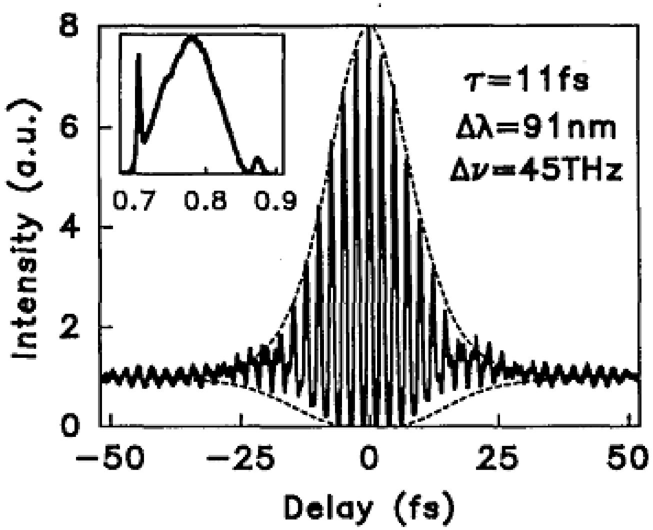
Fig. 3. Computed group delay as a function of wavelength (solid curve) together with experimental data (squares) for the multilayer design of Fig. 1. Note that the absolute delay could not be measured; therefore a wavelength-independent constant delay was added to the measured relative data.

<u>R. Szipőcs,</u> K. Ferencz, Ch. Spielmann, F. Krausz, *Opt. Lett.* 19, pp. 201-203 (1994)

R. Szipőcs, F. Krausz: Dispersive dielectric mirror; U. S. Pat. No.: 5,734,503 (1993)

# MIRROR DISPERSION CONTROLLED Ti:SAPPHIRE LASER



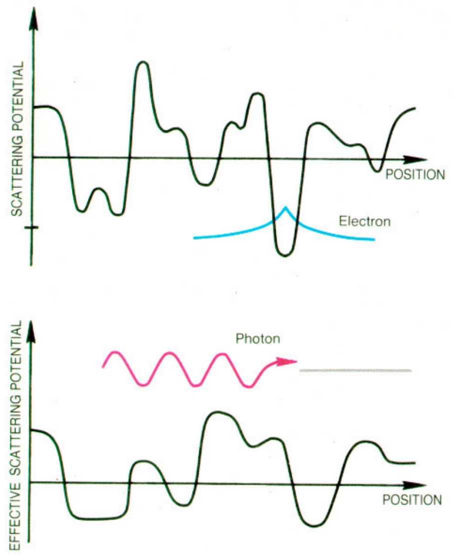


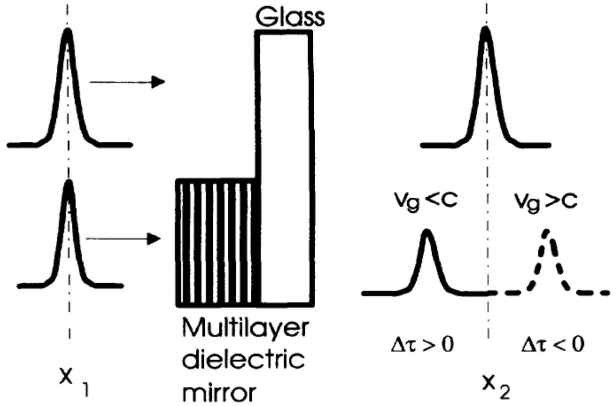
☺ **Highly stable femtosecond pulses with duration of < 10fs**

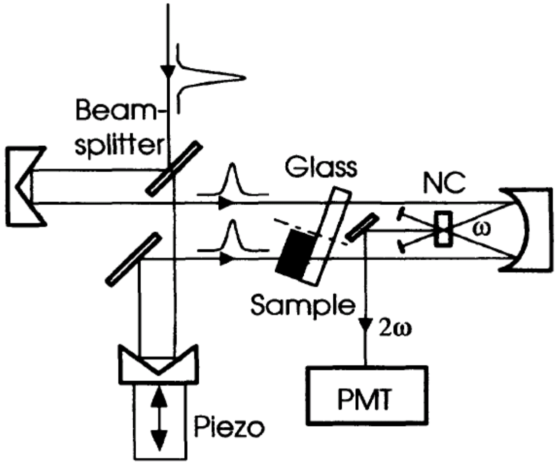
**A.Stingl, Ch. Spielmann, F. Krausz, R. Szipőcs, *Opt. Lett.* 19, pp. 204-206 (1994)**

**R. Szipőcs, F. Krausz: U. S. Pat. No.: 5,734,503 (1993)**

# TUNNELING OF OPTICAL PULSES THROUGH PHOTONIC BANDGAPS





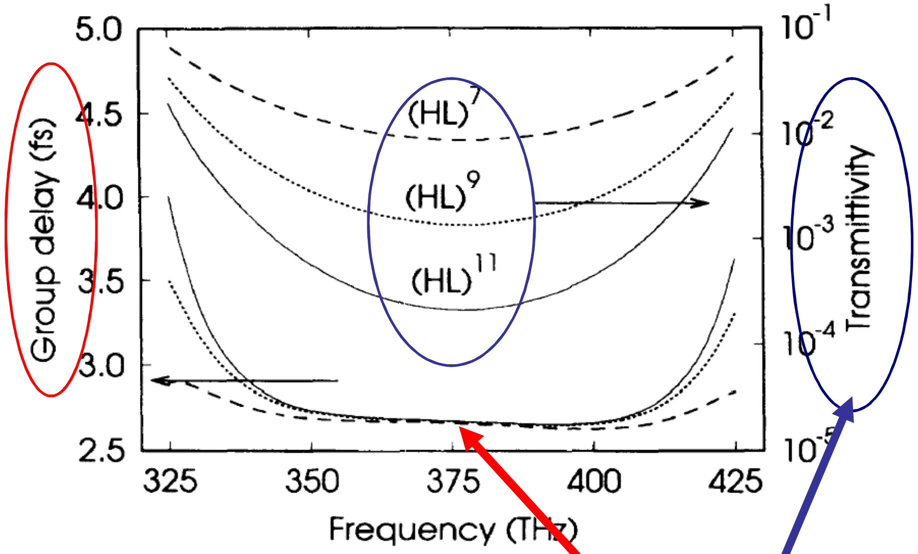


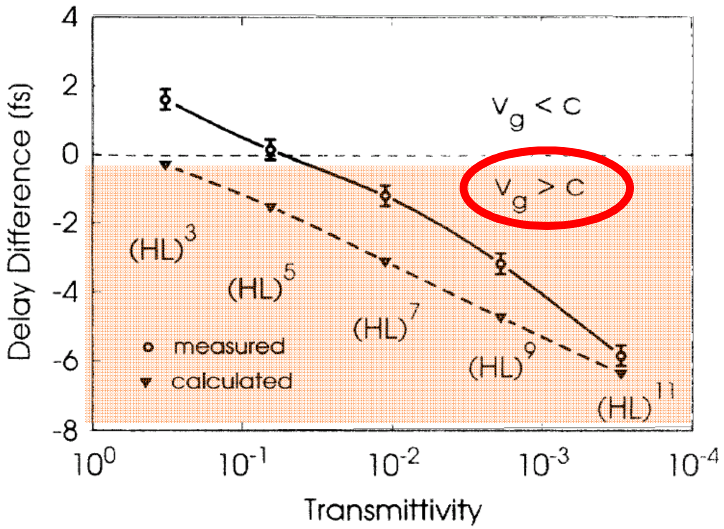
- **Electron tunelling through potential barrier (MacColl, Wigner, Hartmann)**
- **Analogy between the time independent Schrödinger-equation and the Helmholtz-equation**
- **Measuring „tunelling time” by highly stable femtosecond pulses of MDC Ti:sapphire laser**
- **Faster than *c* propagation?**

**A. Steinberg, P.G. Kwiat, and R. Chiao: *Phys. Rev. Lett. 71,* pp. 708-711 (1993)**
**Ch. Spielmann, R. Szipőcs, A. Stingl, F. Krausz: *Phys. Rev. Lett.* 73, pp. 2308-2311 (1994)**

# TUNNELING OF OPTICAL PULSES THROUGH PHOTONIC BANDGAPS

**Photonic bandgap structure samples: substrates / (HL)$^m$ / air**





- **Measured group delay in transmission is INDEPENDENT OF „BARRIER” THICKNESS!**
- **EXPONENTIAL REDUCTION IN TRANSMITTED POWER vs. „barrier” thickness (~ m)**
- **Faster than *c* propagation?**

**Ch. Spielmann, R. Szipőcs, A. Stingl, F. Krausz: *Phys. Rev. Lett.* 73, pp. 2308-2311 (1994)**

# GROUP DELAY AND ABSORPTION LOSS IN A MULTISTACK DIELECTRIC MIRROR

substrate / $0.6(\mathrm{H\ 2L\ H})^9\ 0.5(\mathrm{H\ 2L\ H})^9\ 0.42(\mathrm{H\ 2L\ H})^9$ / air

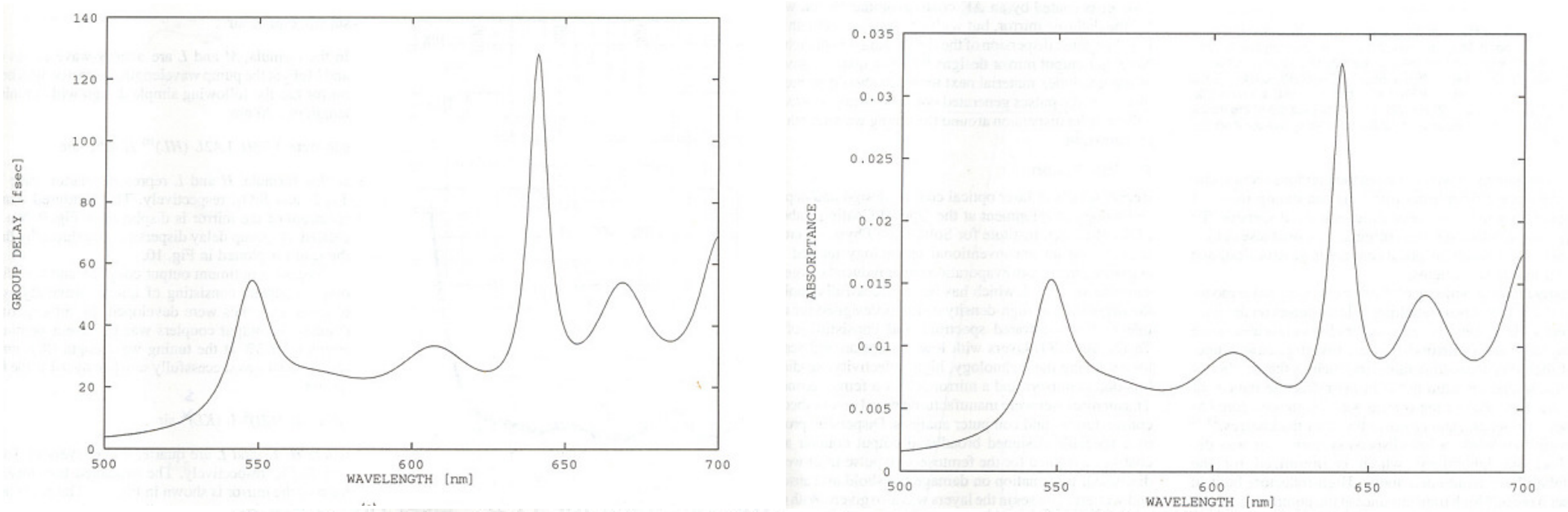
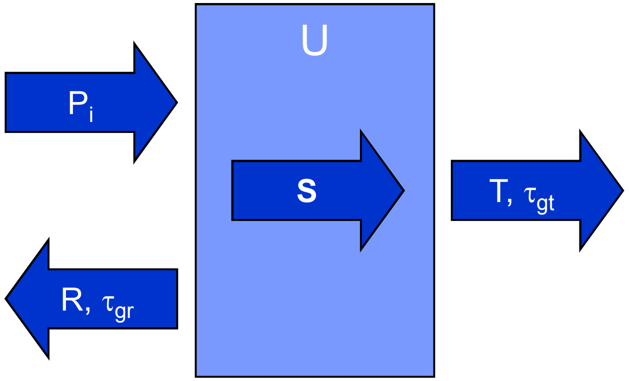


**Fig. 5** Comparison of (a) group delay and (b) absorptance versus wavelength functions of the same mirror design as in Fig. 3, but with $\lambda_0 = 533$ nm. Material dispersion of the $TiO_2$ layers is considered using the Sellmeier dispersion formula: $n(\lambda)^2 = c_0 + c_2/\lambda^2$ ($c_0 = 4.9$, $c_2 = 280{,}000\ \mathrm{nm}^2$). The other refractive indices are $n_S = 1.51$ (BK7), $n_A = 1.0$ (air), and $n_L = 1.45$ ($SiO_2$). For the absorptance computation extinction constants $k_H = 0.0001$ and $k_L = 0.0001$ are used.

- **GROUP DELAY IN REFLECTION IS PROPORTIONAL TO ABSORPTION LOSS**
- **BUT WHY?**

**K. Ferencz, R. Szipőcs**: *Opt. Eng. 32, pp. 2525-2538* **(1993)**

# THEORY (1D) - DIELECTRIC MIRRORS / 1D PBG STRUCTURES



- Contiunity of energy flow (Poyting's theorem):

$$-\oint_S \mathbf{S}(r,t)\mathbf{n}\,da = \frac{dU}{dt}$$

- U is volume integral of energy density *u(r,t)* in the layer structure:

$$u(r,t) = \frac{1}{2}\left(n^2\varepsilon_0 E^2 + \mu_0 H^2\right)$$

- The group delay for reflection and transmission is computed as

$$\tau_{gr} = -\frac{d\phi_r(\omega)}{d\omega}, \qquad \tau_{gt} = \frac{d\phi_t(\omega)}{d\omega}.$$

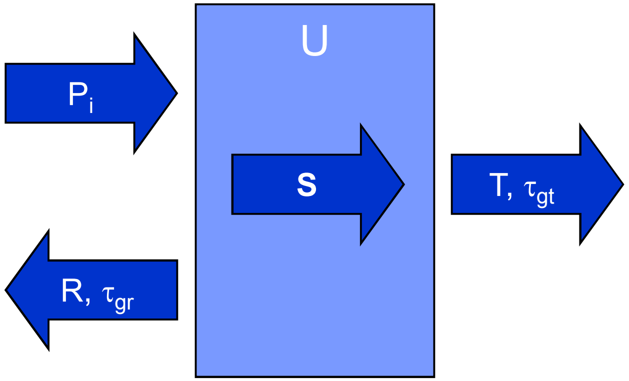
**H. G. Winful: The meaning of group delay in barrier tunneling: a re-examination of superluminal group velocities**
***New Journal of Physics* 8, pp. 101-1 – 101-16 (2006)**

## THEORY (1D) - DIELECTRIC MIRRORS / 1D PBG STRUCTURES

- For low loss layer structure, we get:

$$T \cdot \tau_{gt} + R \cdot \tau_{gr} = \tau_d = \frac{U}{P_i}$$

where $\tau_d$ is the so called dwell time.



For highly reflective (R~1) dispersive dielectic mirror coatings, we can write:

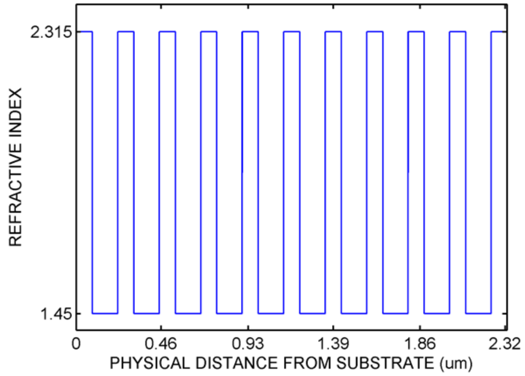
$$\tau_{gr} \approx \frac{U}{P_i}$$

**GROUP DELAY ON REFLECTION IN PROPORTIONAL TO THE ENERGY STORED IN DISPERSIVE DIELECTRIC MIRRORS!**

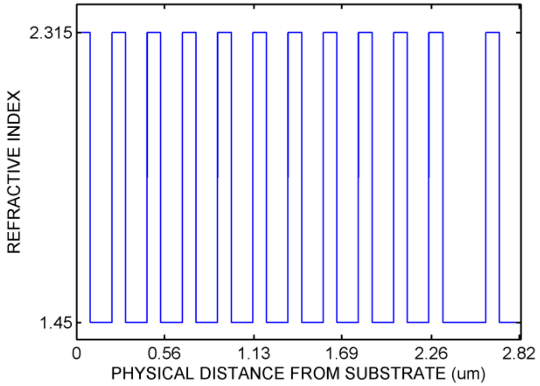
**R. Szipőcs, P. Gy. Antal, "Relation between group delay, energy storage and absorbed/scattered power in highly reflective dispersive dielectric mirror coatings," presented at the *Optical Interference Coatings (OSA), Tucson, AZ, Paper FB3* (2010)**

**P. G. Antal and R. Szipőcs, "Relationships among group delay, energy storage, and loss in dispersive dielectric mirrors," Chin. Opt. Lett., vol. 10, pp. 053101-1–053101-4, 2012.**

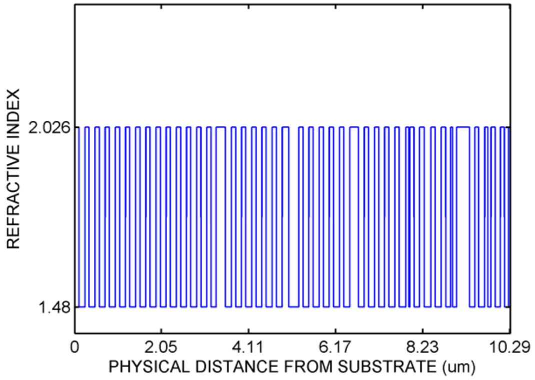
# 1D NUMERICAL EXAMPLES: THE REFRACTIVE INDEX PROFILES



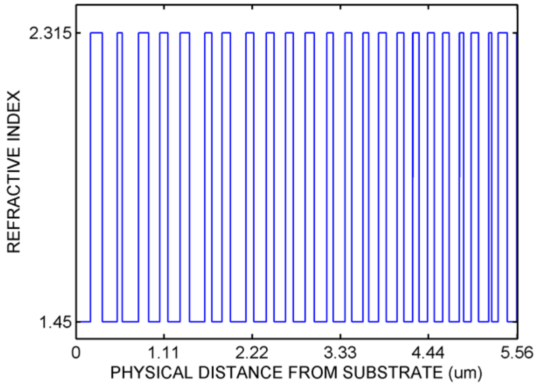
**QW STACK**



**GTI MIRROR**



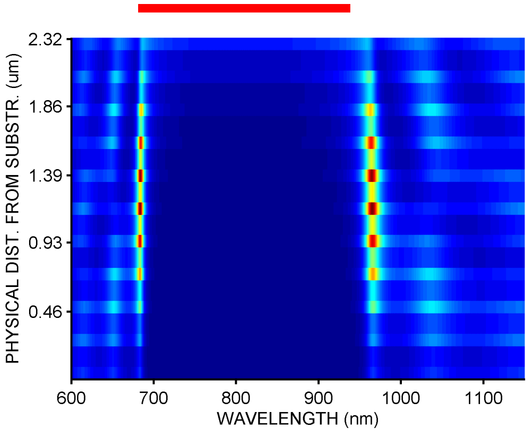
**HIGH-DISPERSIVE MCGTI MIRROR**



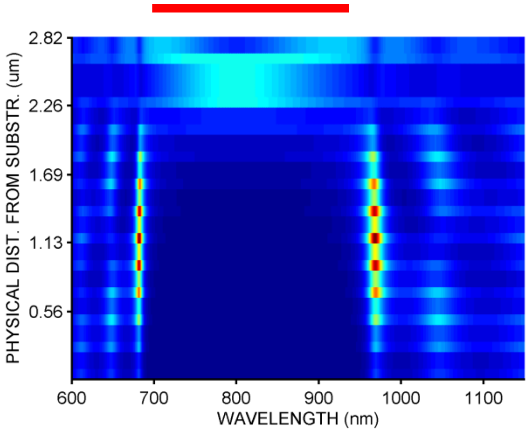
**UBCM MIRROR**

V. Pervak, C. Teisset, A. Sugita, S. Naumov, F. Krausz, A. Apolonski, “High-dispersive mirrors for femtosecond lasers,” Opt. Exp. 16, 10220-10232 (2008).
E.J. Mayer, J. Möbius, A. Euteneuer, W. Rühle, R. Szipőcs, “Ultrabroadband chirped mirrors for femtosecond lasers,” Opt. Lett. 22, 528-530 (1997).

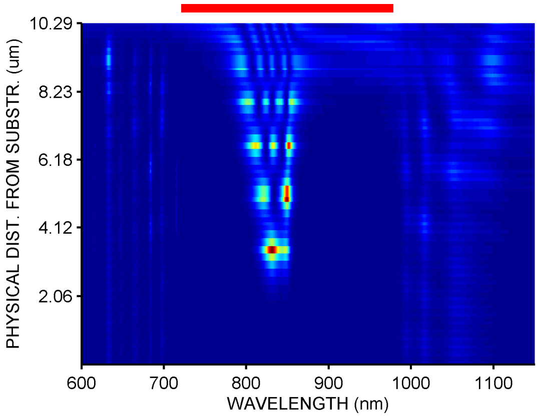
# 1D NUMERICAL EXAMPLES: THE COMPUTED ENERGY DENSITY FUNCTIONS



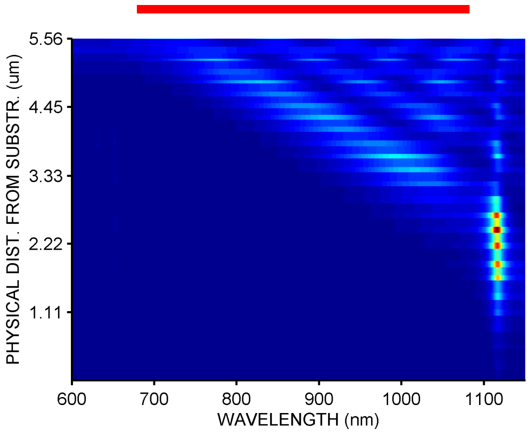
**QW STACK**



**GTI MIRROR**



**HIGH-DISPERSIVE MCGTI MIRROR**



**UBCM MIRROR**

# 1D NUMERICAL RESULTS:
# THE COMPUTED GROUP DELAY, ENERGY STORED AND ABSORBED POWER

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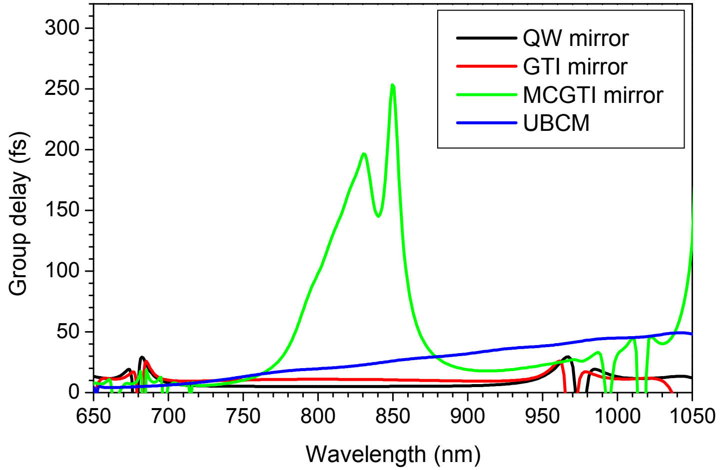
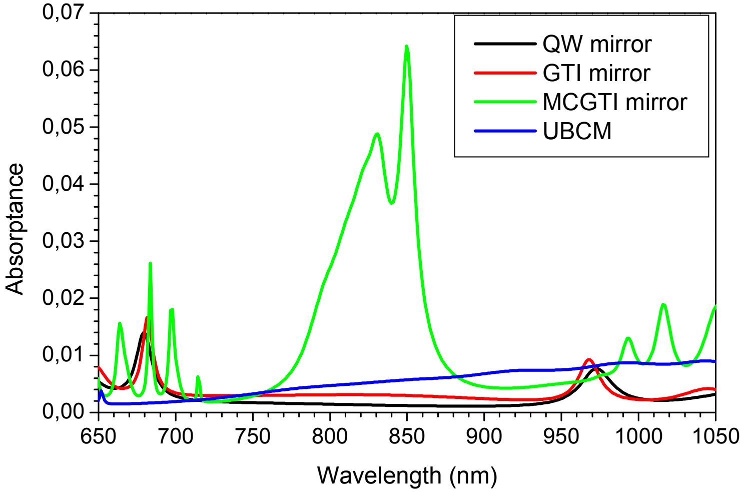
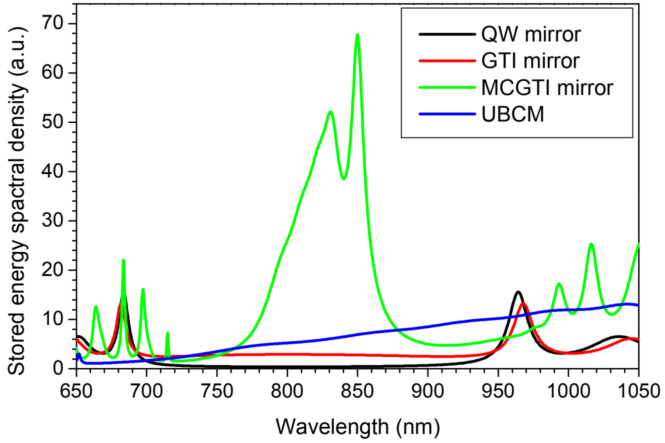






For computing absorptance, a wavelength independent k = 0.0001 extinction constant was used for both H and L layers.

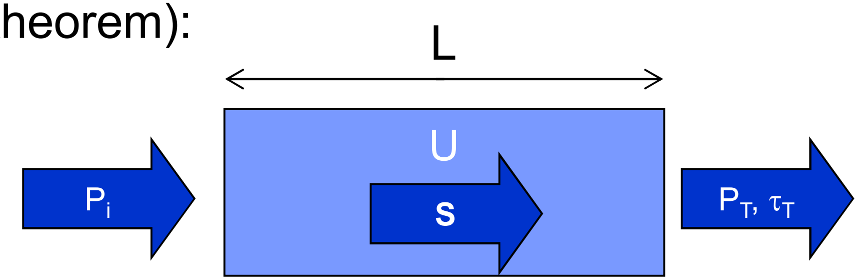
**TWO ORDERS OF MAGNITUDE HIGHER ABSORPTION FOR THE HIGH-DISPERSIVE MCGTI MIRROR STRUCTURE!** ☹

Loss can be reduced by state of the art deposition technologies. ☺

## THEORY (2D) - OPTICAL FIBERS

- Contiunity of energy flow (Poyting's theorem):

$$-\oint_s S\hat{n}\,\mathrm{da} = \frac{\mathrm{dU}}{\mathrm{dt}}$$



- Stored energy (U) is volume integral of energy density *u(x,y,z)* in the fiber:

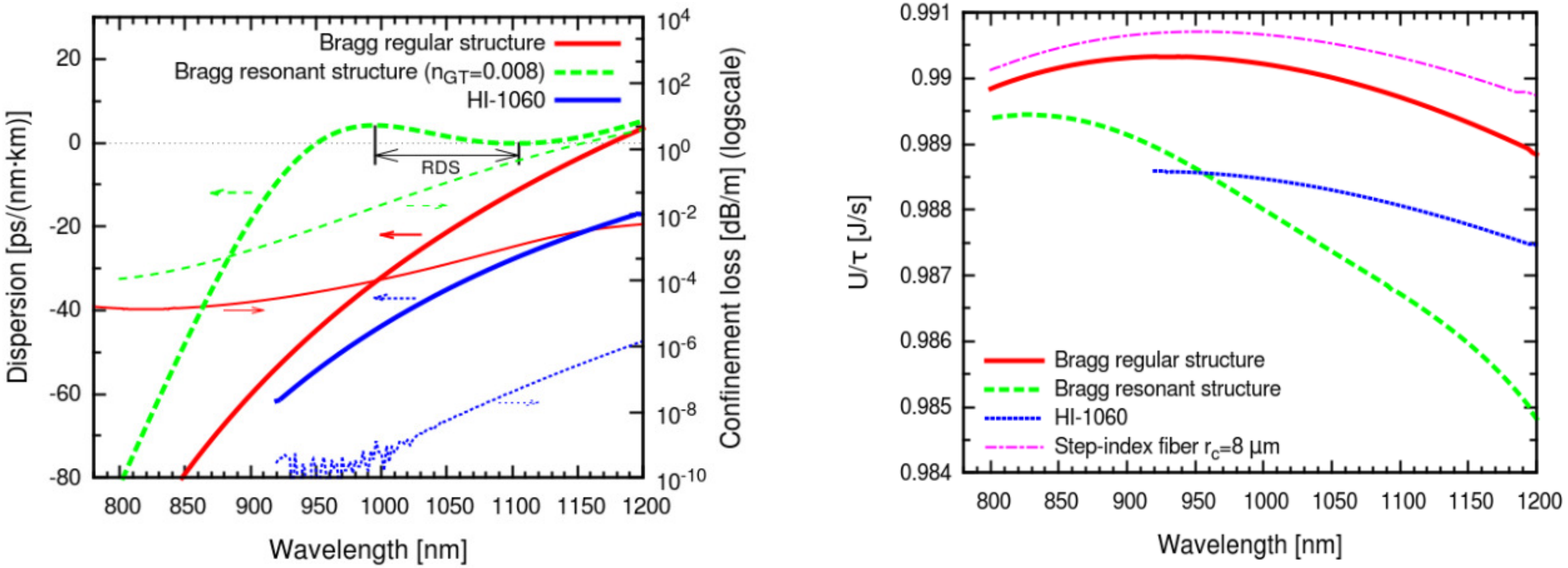
$$\mathrm{U} = \iiint u\,dV = \iiint \left(\frac{1}{2}\varepsilon E^2 + \frac{1}{2}\mu H^2\right) dV$$
$$= \frac{L}{2}\iint \left(\varepsilon_o n^2 E^2 + \mu_o H^2\right) dA$$

- The group delay ($\tau$) for transmission is computed as

$$\tau = \frac{\mathrm{d}\phi}{\mathrm{d}\omega} = \frac{d}{\mathrm{d}\omega}\left(\frac{\omega \mathrm{L}}{c} n_{\mathrm{eff}}(\omega)\right)$$

Z. Várallyay, R. Szipőcs *„Stored Energy, Transmission Group Delay and Mode Field Distortion in Optical Fibers,"*
**IEEE J.STQE Vol. 20, No. 5, SEPTEMBER/OCTOBER (2014), in press**

# NUMERICAL RESULTS – OPTICAL FIBERS



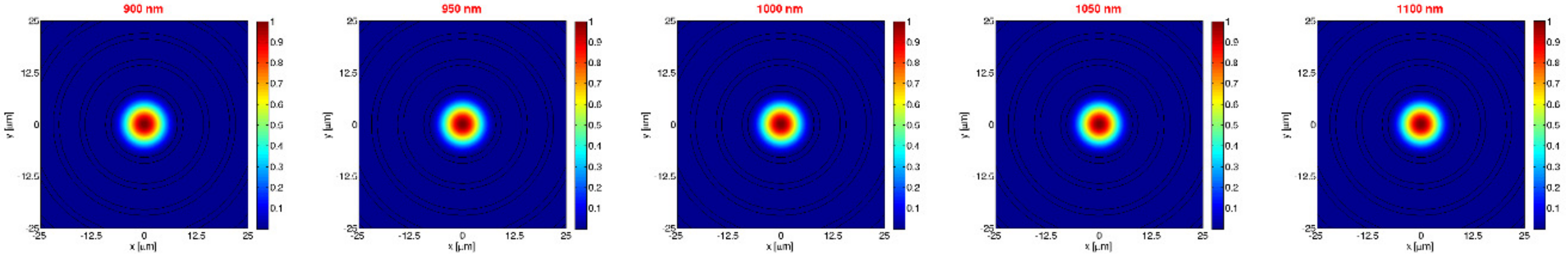
(a) (b)

(a) Computed **dispersion vs. wavelength functions (thick lines), corresponding confinement losses (thin lines) and (b) computed stored energy-group delay ratio (U/τ) vs. wavelength functions** of solid core PBG fibers of two differen designs and of two different index-guiding fibers. One of the index guiding fibers is similar to HI-1060 of Corning, while the second one has an 8 µm core radius. Each fiber has a unit length of 1 m and the incident power is 1W.

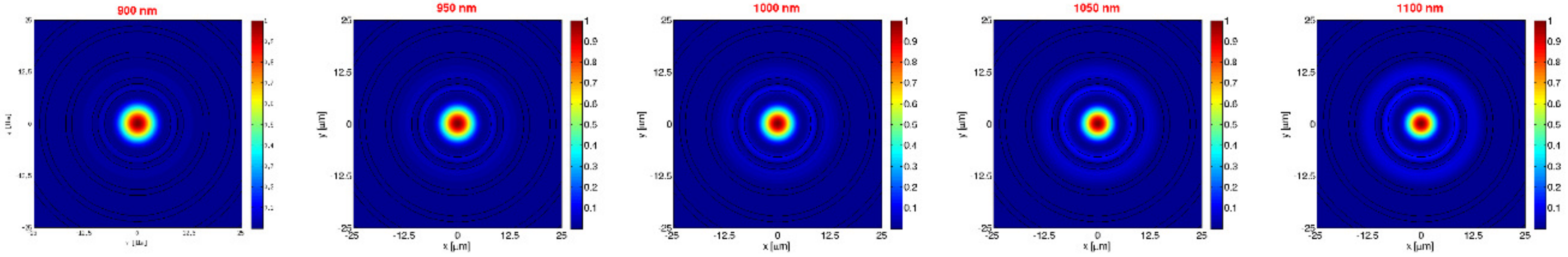
**Z. Várallyay, R. Szipőcs *„Stored Energy, Transmission Group Delay and Mode Field Distortion in Optical Fibers,”***
**IEEE J.STQE Vol. 20, No. 5, SEPTEMBER/OCTOBER (2014), in press**

# NUMERICAL RESULTS – OPTICAL FIBERS

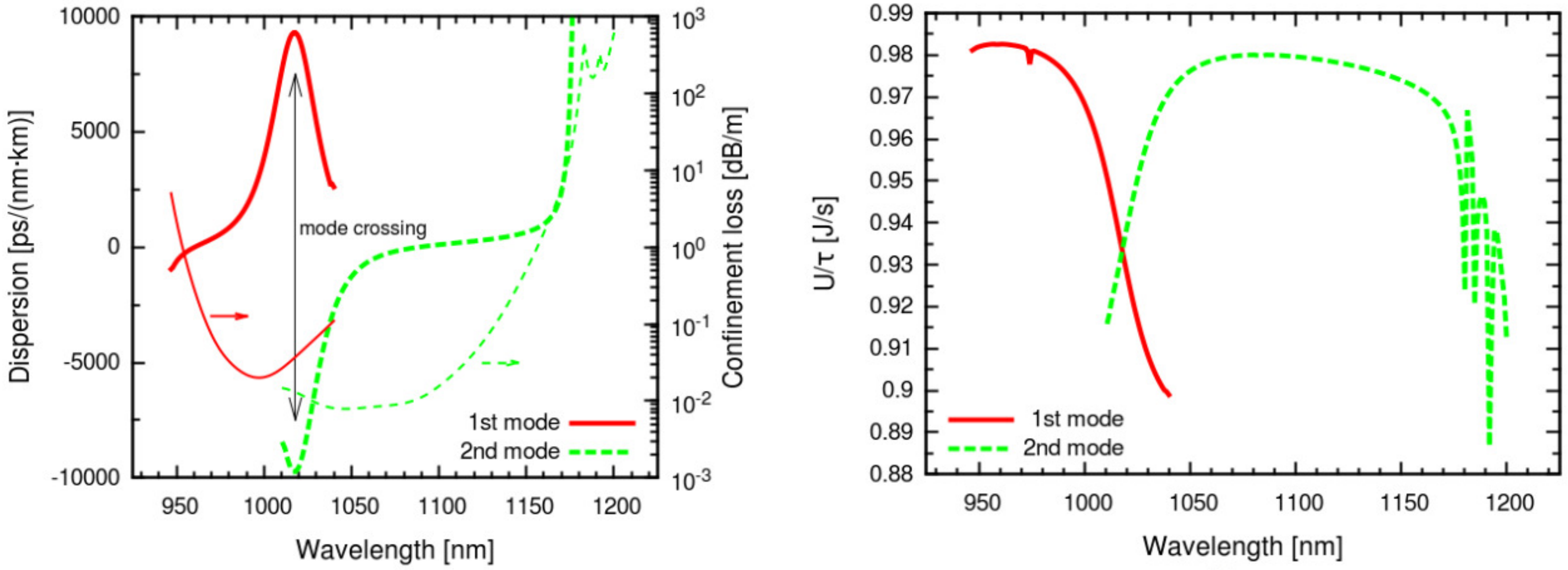
Mode profiles in a regular Bragg structure:



Mode profiles in a Bragg structure having a resonant circular layer around the core with $\delta n_{GT}$= 0.008:



# NUMERICAL RESULTS – OPTICAL FIBERS

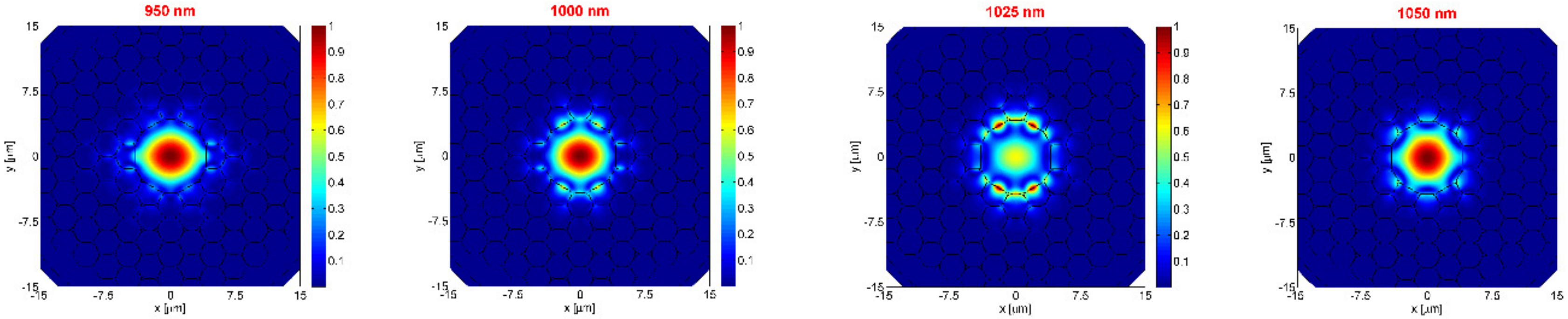


(a) (b)

**(a) Dispersion vs. wavelength functions (thick lines), corresponding confinement loss values (thin lines) computed for the two fundamental modes in the HC-1060 type fiber and (b) computed U/τ ratios for the two modes.** Long wavelength edge of the 1st mode bandgap and the short wavelength edge of the 2nd mode bandgap can be observed in the dispersion vs. wavelength functions as well as in the U/τ curves at wavelengths where the U/τ value drops quickly (at around 1020 nm).

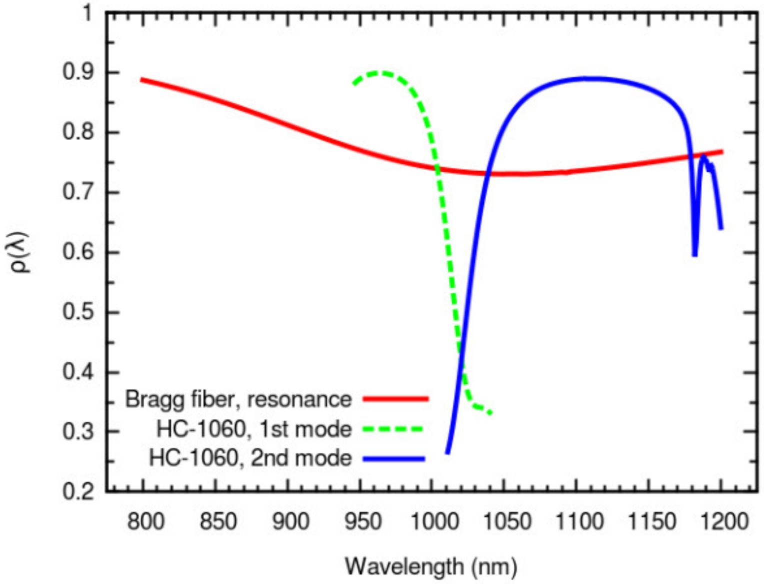
**Z. Várallyay, R. Szipőcs *„Stored Energy, Transmission Group Delay and Mode Field Distortion in Optical Fibers,”***
**IEEE J.STQE Vol. 20, No. 5, SEPTEMBER/OCTOBER (2014), in press**

# Energy, Transmission Group Delay and Mode Field Distortion in Optical Fibers



(a) (b) (c) (d)

Fundamental mode profiles in the core of a HC-1060 fiber at (a) 950, (b) 1000, (c) 1025 and (d) 1050 nm. The mode profiles shown in Figs. (a) and (b) correspond to the so-called first mode, while those shown in Figs. (c) and (d) correspond to the second mode.



## Focusability ρ(λ) defined as:

$$\rho(\lambda)=\frac{\int_0^k \int_0^{2\pi} \tilde{I}(k_r, k_\phi, \lambda)^2 \, d k_\phi \, d k_r}{\int_0^k \int_0^{2\pi} \tilde{I}_0(k_r, k_\phi, \lambda)^2 \, d k_\phi \, d k_r}$$

Focusability ρ(λ) of the propagating fundamental modes calculated for a reversed dispersion slope, resonant Bragg fiber (red curve) and for a hollow core PBG fiber (green and blue curves) near resonance and leaking mode wavelengths.

# CONCLUSION

- **Dispersive (or chirped) mirrors:** Since the reflection group delay is proportional to the energy stored in highly reflective multilayer structures, the higher group delay goes together with higher absorption/scattering losses, that should result in **reduced damage threshold for highly dispersive mirror devices.**

- **Dispersive optical fibers.** We found that **the $U/\tau$ ratio is very close to unity all over the fiber transmission band**, furthermore, the lower confinement loss increases the energy-group delay ratio close to unity.

- Since the stored energy in the fiber is derived from the electric field distributions at each wavelength, we learned that **modifications in the dispersion function of any optical fiber always result in a change in the mode field distribution at each wavelength, and vice versa**. As a consequence, **dispersion tailored optical fibers**, such as HOM fibers having a desired group-delay dispersion functions **have a reduced focusability** of the collimated laser beam, which can be a critical issue in fiber integrated nonlinear microendoscope systems for instance.